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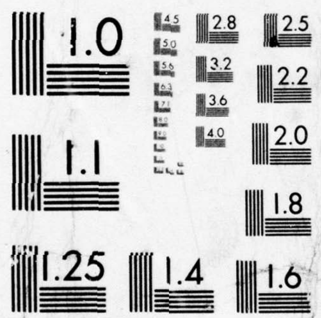

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UPPER-ATMOSPHERE ZONAL WINDS: VARIATION WITH HEIGHT AND LOCAL TIME.

by

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SUMMARY

The average rotation rate of the upper atmosphere can be found by analysis of the changes in the orbital inclinations of satellites, and results previously obtained have indicated that the atmospheric rotation rate appreciably exceeds the Earth's rotation rate at heights between 200 and 400km.

This report examines ~~We have examined~~ all such results previously published in the light of current standards of accuracy: some are accepted, some revised, and some rejected as inadequate in accuracy. ~~We~~ also are analysed a number of fresh orbits and, adding these to the accepted and revised previous results, ~~we derive~~ the variation of zonal wind speed with height and local time is derived. The rotation rate (rev/day) averaged over all local times increases from near 1.0 at 150km height to 1.3 near 350km (corresponding to an average west-to-east wind of 120m/s), and then decreases to 1.0 at 400km and probably to about 0.8 at greater heights. The maximum west-to-east winds occur in the evening hours, 18-24h local time: these evening winds increase to a maximum of about 150m/s at heights near 350km and decline to near zero around 600km. In the morning, 4-12h local time, the winds are east to west, with speeds of 50-100m/s above 200km. It is ~~We~~ also tentatively concluded that, at heights above 350km, the average rotation rate is greater in equatorial latitudes (0-25 deg) than at higher latitudes.

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CONTENTS

1 INTRODUCTION

The west-to-east rotation of the upper atmosphere subjects a satellite to an aerodynamic force normal to its orbit, and this force produces a small decrease in the orbital inclination i during the course of its life. If the change in i is accurately measured, and other perturbations are removed, the rotation rate of the upper atmosphere in the region near the satellite's perigee can be determined. The first such analysis[1], using Sputnik 2, indicated that the atmosphere at heights near 200km might be rotating faster than the Earth, a finding confirmed by analysis of the orbit of Sputnik 3 rocket[2]. Results from nine satellites in the early 1960s suggested west-to-east winds averaging about 150m/s in the 200-300km height range[3]. In 1970 results from 32 satellites were combined[4], indicating that the rotation rate Λ (rev/day) increased from 1.1 at 200km to 1.4 at 350km height. (The west-to-east wind at a representative latitude near 30° is approximately $400(\Lambda - 1)$ m/s, so that $\Lambda = 1.4$ implies a wind of about 160m/s.) In 1971 the analysis of the orbit of Ariel 3 at 500km revealed a low rotation rate[5], so the picture presented[6] in 1972 was of Λ increasing from 1.1 at 200km to 1.4 at 350km, and then decreasing to perhaps 0.7 at 500km.

These conclusions depended on observational results of varied accuracy and reliability, many of which were analysed before the possible effects of orbital resonances were appreciated. So we thought that the existing results should be critically re-examined in the light of current standards, and if necessary re-analysed, removing the effects of perturbations previously ignored. The outcome of our scrutiny of the existing results is as follows:-

(1) We discard about 30%, because they do not meet current standards of accuracy, although some orbits, including those of Sputniks 2 and 3, will be worth redetermining.

(2) About 30% are accepted unchanged.

(3) About 40% have been revised, chiefly by making allowance for perturbations at resonances, and also by examining the possibility of dependence on local time. Most of the revised values prove to be within the standard deviations previously quoted.

In addition we have analysed five fresh orbits and included all results that come up to standard. In our final diagram we also include results on balloon satellites by Blum and Schuchardt[7], and by Slowey[8], and results on short-lived satellites by Forbes[9].

2 METHOD

2.1 Theory

An orbit of eccentricity $e < 0.2$ immersed in an oblate atmosphere rotating at Λ rev/day suffers a change Δi in inclination given by[10]

$$\frac{\Delta i}{\Delta T_d} = \frac{\Lambda \sin i}{6\sqrt{F}} \left[1 + \frac{I_2}{I_0} \cos 2\omega - 2e \frac{I_1}{I_0} \left\{ 2 + \left(1 + \frac{I_2}{I_0}\right) \cos 2\omega \right\} \right.$$

$$\left. + \tfrac{1}{2} c \left\{ 1 - \frac{I_2^2}{I_0^2} + \left(\frac{I_4}{I_0} - \frac{I_2^2}{I_0^2} \right) \cos 4\omega \right\} + O(c^2, e^2) \right] . \qquad (1)$$

In equation (1), T_d is the orbital period in days, and ΔT_d is the change in T_d due to drag; I_n is the Bessel function of the first kind and imaginary argument, of degree n, and its argument is $z = ae/H$, where a is the semi major axis and H is the density scale height; $\sqrt{F}$ is a factor[10] that is usually between 0.95 and 1.0; ω is the argument perigee; and $c = \{\varepsilon a(1 - e) \sin^2 i\}/2H$, where ε is the ellipticity of the atmosphere, taken as 0.00335.

If $z > 10$ (which usually means that $e > 0.05$), the Bessel functions in (1) may be replaced by their asymptotic expansions to give

$$\frac{\Delta i}{\Delta T_d} = \frac{\Lambda \sin i}{3\sqrt{F}} \left\{ (1 - 4e) \cos^2 \omega - \frac{1}{z} \cos 2\omega + \frac{\varepsilon}{e} (1 - e) \sin^2 i \sin^2 2\omega \right.$$

$$\left. + O\left(e^2, c^2, \frac{1}{z^2}\right) \right\} . \qquad (2)$$

This equation is of adequate accuracy only over a rather narrow, though important, range of values of e – usually $0.05 < e < 0.15$. Despite this limitation, equation (2) is most useful in showing three important features of the variation in i:

(a) the build-up of Δi as ω goes through many cycles, and $\cos^2 \omega$ tends to average out at 0.5;

(b) the increased effect of atmosphere oblateness when e is small; and

(c) the bias towards equatorial latitudes - because $\cos^2 \omega$ decreases from 1.0 when perigee is at the equator to zero when perigee reaches latitude i. It is useful to define a latitude, ϕ say, to take as the maximum latitude up to which zonal winds are effective in altering i ; we take ϕ to be the perigee latitude for which $\cos^2 \omega = \frac{1}{3}$ (i.e. $\sin \phi = 0.816 \sin i$) .

Meridional winds also produce changes in inclination, and when the Bessel functions are again expanded in powers of $1/z$ for simplicity, the change Δi is given by[11]

$$\frac{\Delta i}{\Delta T_d} = -\frac{\mu \cos i}{3} \left\{\frac{2}{F(1 + \cos^2 i)}\right\}^{\frac{1}{2}} \left\{\left(1 + \frac{K}{4}\right)\left(1 - \frac{1}{2z}\right) \cos \omega - \frac{K}{4} \cos 3\omega + 0\left(0.1, \frac{1}{z^2}\right)\right\} \quad (3)$$

where $K = \sin^2 i/(1 + \cos^2 i)$ and μ is the equivalent south-to-north atmospheric rotation rate, i.e. the south-to-north wind at perigee height y_p is $(464 + 0.073y_p)\mu$ m/s. Equation (3) may be assumed to apply for $0.05 < e < 0.2$, and it shows that if μ is constant, or symmetrical about the equator, or antisymmetrical about the equator, the net effect of meridional winds is virtually zero when ω , and hence $\cos \omega$, goes through several cycles. If ω varies over less than half a cycle, however, the effects of meridional winds need to be examined (except for near-polar satellites, for which the effects are small).

Though equations (2) and (3) apply for $e < 0.2$, the corresponding equations for $e > 0.2$ have been derived[12], and lead to similar conclusions.

The effective height at which Λ is being evaluated has been discussed in Ref.13: for an orbit of eccentricity >0.01, the effective height y may be taken as 0.75H above perigee. This is subject to errors of perhaps 0.2H (about 10km), but since $|d\Lambda/dy| < 0.004\text{km}^{-1}$, a change of 10km in y corresponds to change of <0.04 in Λ , and the resulting uncertainty in Λ is always less than the standard deviation in Λ .

2.2 Details of procedure

Many of the orbits analysed have been determined at RAE, using the PROP orbit refinement program[14,15], with optical and radar observations; but a number of orbits determined by the US Navy, the Smithsonian Astrophysical Observatory and NASA are also used. The perturbations caused by lunisolar gravitational attraction, and by the zonal harmonics in the geopotential, have when necessary been removed by numerical integration, usually at one-day intervals, using the PROD computer program[16].

When an orbit passes through the condition of 15th-order resonance with the Earth's gravitational field, with the track over the Earth repeating after 15 revolutions of the satellite, there may be an appreciable variation in inclination as a result of perturbations from 15th-order harmonics in the geopotential. These perturbations have been removed, whenever necessary, by applying the THROE computer program[5], and using the values of 15th-order harmonic coefficients obtained from analysis of such resonances on low-drag satellites[17]. Some of the orbits also experience 14th-order resonance, and when necessary the variation in inclination is fitted using THROE, and allowed for.

The theoretical variation of i due to atmospheric rotation is calculated for a series of values of Λ, using a computer program (ROTATM) based on an extended version[18] of equation (1), which includes terms in e^2 and c^2. The interval of integration is chosen to be small enough to avoid significant errors due to the finite interval. For many of the satellites, steps of integration were taken at the times when $\omega = 0, 22.5^\circ, 45^\circ \ldots$.

The observational values of i for each satellite are then fitted as closely as seems reasonable with appropriate theoretical curves. The most difficult problem is to select the points at which the value of Λ should be altered: the choice of the value of Λ over a specified time interval is usually fairly clear. Nearly all the fittings have so far been made by eye, since there are usually too few points for statistical procedures. We try to make realistic error estimates by assessing the likely errors in i at the beginning and end of each section of the curve, σ_B and σ_E, say, and then taking $\dfrac{\Lambda\sqrt{\sigma_B^2 + \sigma_E^2}}{i_B - i_E}$ as the standard deviation in Λ. In making these assessments of σ_B and σ_E, the fact that i is continuous often allows a reduction in the estimated errors when the end of one section of the curve leads straight into the beginning of the next section. For three of the satellites the variations in inclination have been fitted by the least-squares method, but the formal standard deviations have been increased (usually by factors near 2) to conform with the standards adopted for other values of Λ. The individual fittings are discussed in sections 3 and 4.

3 VALUES OF ROTATION RATE AVERAGED OVER LOCAL TIME

3.1 General

Long-lived satellites, which go through many cycles in local time and argument of perigee, have several advantages. With very few exceptions (such as Sun-synchronous orbits) the values of rotation rate obtained are (a) averaged over all local times, (b) most unlikely to be appreciably influenced by meridional winds, and (c) averaged over latitudes between the equator and the latitude ϕ defined in section 2.1. Conditions (a), (b) and (c) apply for all the satellites discussed in sections 3.2 to 3.17.

The disadvantages of the long-lived satellite are that the orbit usually has to be determined for several years, and that it may pass through resonances with the Earth's gravitational field rather slowly, so that changes in i at resonance may be appreciable.

3.2 Explorer 1, 1958α

Explorer 1, the first US satellite, was in orbit from January 1958 until May 1970, and is unique in having experienced two maxima of solar activity, including the highest recorded maximum of early 1958. Fig.1 summarizes the results of the orbital analysis of Explorer 1 by Walker[19]: the values of inclination have been cleared of significant perturbations; the variations at 14th and 15th-order resonance were calculated and found to be small. The observational values are well fitted by a theoretical curve divided into three sections: $\Lambda = 1.5 \pm 0.1$ for a height of 400km in the high solar activity from 1958 to mid 1960; $\Lambda = 1.2 \pm 0.1$ for a height of 380km during the years of lower solar activity 1961-67; and $\Lambda = 1.3 \pm 0.1$ for a height of 355km during the second solar maximum in 1968-70.

3.3 Transit 1B, 1960γ2

The orbit of Transit 1B during its protracted 15th-order resonance in 1962, and at intervals from then until the end of the life, has been analysed by Hiller and King-Hele[20], using orbits determined from optical observations, including a number from the Hewitt and Baker-Nunn cameras. The atmospheric rotation rate previously given, from the end of the resonance to decay in 1967, was $\Lambda = 1.35 \pm 0.1$. Reassessment of the initial value of i, giving less weight to the end-point of the fitted resonance curve, suggests that the initial value of i should be slightly lower. The resulting revised value of Λ is 1.30 ± 0.1, at a height of 360km. Fig.2 shows the values of i and the theoretical curve. Though there are only nine observational values, those in 1967 are extremely accurate and define the end-point firmly. Curves for $\Lambda = 1.0$ and $\Lambda = 1.6$ are shown as broken lines.

3.4 Ariel 1, 1962o1

Ariel 1 was launched on 26 April 1962 into an orbit inclined at 53.9° to the equator with an initial period of 100.9 minutes. Between 1962 and 1973 the period decreased by more than 5 minutes and it seemed worth analysing the variation in inclination over these 11 years, using the four groups of values plotted in Fig.3.

The first group comes from the orbits obtained by Merson and Tayler[21] using the RAE orbit determination program on the Pegasus computer with Minitrack observations. These values have been converted to the same definition as the later values[14] by adding $\frac{1}{8}J_2\left(\frac{R}{p}\right)^2 \sin 2i(3 + 4e\cos\omega)$. Lunisolar and zonal harmonic perturbations have been removed using the PROD computer program. The first inset in Fig.3 shows the individual values as circles, with triangles representing the means of groups of values. The triangles are replotted above, on the main graph, on the smaller scale.

The second group of values is from US Navy orbits near the time of the 29:2 resonance in November 1969, when the decay under the action of air drag carried the orbit through the condition when the tracks over the Earth repeat every two days after 29 revolutions. These values, with lunisolar and zonal harmonic perturbations removed, are plotted as circles in the second inset graph. The values revealed a substantial perturbation near the date of 29:2 resonance, which is being analysed separately and will be reported elsewhere. The net effect of the resonance perturbation is an increase in inclination of about 0.003°. This is allowed for by an appropriate break in the fitted theoretical curve, as shown in the inset and in the main graph. The effects of the 29:2 resonance have never before been clearly shown. They are visible here (a) because this is a low-drag orbit, and (b) because of the excellent accuracy of the US Navy values.

The third group is a set of US Navy values from early 1971: after removal of lunisolar and zonal harmonic perturbations, these values are plotted as circles in the third inset graph; the triangles, indicating the mean values of selected groups, are replotted on the main graph.

The fourth and final group of values comprises the accurate orbits obtained by Walker[22] from Hewitt camera, visual and US Navy observations near 15th-order resonance. A correction of -0.002° has been made to bring the lunisolar correction to the same phase as for the other values, and the atmospheric rotation perturbation, previously removed[22], has been restored.

As Fig.3 shows, these values of inclination are well fitted by a theoretical curve with $\Lambda = 1.1$ from 1962 to 1969, and again with $\Lambda = 1.1$ from 1969 to 1973. The uncertainties in the values of i at the beginning and end of the first section are assessed as 0.001° and 0.0015°, giving $\Lambda = 1.1 \pm 0.15$, at a height of 420km, for solar activity which runs through solar minimum up to solar maximum. For the second value of Λ, the total uncertainties in the initial and final values of i are assessed as 0.0015° and 0.001° on a decrease of 0.019°, so that $\Lambda = 1.1 \pm 0.1$, at a height of 400km for fairly high solar activity.

3.5 1962βτ1 and 1962βτ5

These two satellites are taken together because of the similarity of their orbits and mass/area ratios. Both were spheres 0.6m in diameter with masses of 23kg, and they were launched on 13 December 1962 into orbits inclined at 70.4° to the equator, with perigee height near 230km and apogee height near 2800km. Both remained in orbit for over 4 years, and their decays were only 4 days apart: 1962βτ5 decayed on 5 February 1967, and 1962βτ1 on 9 February 1967.

We have re-examined the observational data for these satellites, and we see no reason to revise the values chosen previously for the atmospheric rotation rate[23]. The accuracy of the orbital elements is poor by current standards, with standard deviations of order 0.01°; but both satellites suffered decreases in inclination of about 0.17°, so it is still possible to obtain quite good values of the average atmospheric rotation rate.

For 1962βτ1 the value previously obtained, from the beginning of 1965 until decay, was $\Lambda = 1.3 \pm 0.1$rev/day. Re-examination of the data (to be seen in Fig.2 of Ref.23) shows that the fit was not very good early in 1966, and 14th-order resonance occurred in March 1966. From comparison with 1962βτ2 (see section 3.6) it seems unlikely that the change in inclination at resonance exceeded 0.005°, which is less than the scatter in the values. So no change in Λ is needed, but we reassess the standard deviation as 0.15, giving $\Lambda = 1.30 \pm 0.15$.

For 1962βτ5 there is no sign of any misfitting at the 14th-order resonance, though again the change would be less than the errors in the values. After scrutiny of the data (Fig.1 of Ref.23), which extend from 1962 to 1967, we retain the same value of Λ , but reassess the error in the rotation rate at 10%, giving $\Lambda = 1.30 \pm 0.13$.

Since these values come from satellites with almost identical histories of perigee distance, and yet are quite independent (the satellites having pursued independent paths through the atmosphere for four years), the two values can appropriately be combined into one. This gives a combined atmospheric rotation rate of 1.30 ± 0.10rev/day for the years of low solar activity, 1963-1966 (and early 1967) for a mean height of 250km.

3.6 Injun 3, 1962$\beta\tau$2

Injun 3 was one of the satellites in the multiple launch on 13 December 1962: it entered an orbit similar to 1962$\beta\tau$1 and remained in orbit for more than 5 years, decaying on 25 August 1968. Up to 1967 the orbits available are much more accurate than for the other satellites in the 1962$\beta\tau$ launch, because Injun 3 was tracked by the NASA Minitrack interferometers during its first year in orbit, and by the Baker-Nunn cameras of the Smithsonian Astrophysical Observatory up to about 1967. During the first year the orbits from both NASA and SAO are very good, and there are also some excellent groups of SAO orbits at later dates when the Baker-Nunn camera observations were sufficiently numerous.

In our previous analysis we obtained a value of rotation rate up to May 1967, and another value from June 1967 to the end of the life, from elements given in prediction bulletins. After scrutinizing the data again, we decided to discard these later orbits as being insufficiently accurate; but fortunately we were able to obtain US Navy orbits from August 1967 onwards, from which a good value of rotation rate could be derived.

The main part of Fig.4 shows the NASA and SAO values of inclination from launch until May 1967, with a fitted theoretical curve for a rotation rate of 1.3rev/day, after removal of a small number of individual values which are more than 0.02° from the curve. Over 200 points are plotted in this part of Fig.4: the orbits and the fit are both very good. The values during 1965 are rather scattered, but this is of no consequence, since removal of the values in 1965 would not affect the results.

Injun 3 experienced 14th-order resonance on 4 September 1967, and the variation in inclination at resonance has been analysed, using the THROE computer program with US Navy elements. Details of the analysis will be published elsewhere; here we need only note that the theoretical curve fits well (see small diagram at top of Fig.4), and that the inclination decreases by 0.005° as a result of passing through 14th-order resonance. Injun 3 also experienced 13th-order resonance, in 1965, when the orbits were sparse and at their least accurate. There is no sign of any appreciable change in inclination at 13th-order resonance, but the possibility of a change of order 0.005° cannot be ruled out. Because of the large number of accurate orbits near the end-points in Fig.4, the error in the curve at the end-points is likely to be less than 0.005°, and the neglect of the possible change at 13th-order resonance effect must be regarded as the major source of error. Since the overall decrease in inclination is 0.07°, an error of 0.005° gives a standard deviation in Λ of 7%. So the rotation rate determined from Injun 3 during the low solar activity between 1963 and 1967 is 1.3 ± 0.1 rev/day, for a height of 260km.

The small diagram at the top of Fig.4 shows the variation in inclination during and after 14th-order resonance, as given by the US Navy orbits. During the resonance, the perturbation due to atmospheric rotation is removed from the values, taking $\Lambda = 1.3$. Then at MJD 39791 there is a return to normal values, with the end-point of the curve fitted at resonance being taken as the initial value for the subsequent $\Lambda = 1.2$ curve, which fits the points quite well up to 15th-order resonance in May 1968. Analysis of the 15th-order resonance is not practicable, but the effects should be smaller than at 14th-order resonance, because the drag is more than twice as great. After the 15th-order resonance the values of inclination become less accurate, but the curve is still acceptable. Assessing the errors in the usual manner, we find $\Lambda = 1.2 \pm 0.1$ between October 1967 and May 1968, for a height of 255km. The local time during the main decrease in inclination can be regarded as 'average', since it runs from 18h through midnight to 12h, and therefore samples equally both the evening (18-24h) and morning (4-12h) extremes.

3.7 Injun 3 rocket, 1962βτ6

Numerous orbits of 1962βτ6 between 1965 and 1968 were determined at RAE using the PEGASUS and PROP computer programs with visual and kinetheodolite observations[24-26]. Fig.5 shows selected values of inclination from these orbit determinations, after removal of lunisolar and zonal harmonic perturbations, and with $\frac{1}{8}J_2\left(\frac{R}{p}\right)^2 \sin 2i(3 + 4e\cos\omega)$ added to the PEGASUS values to conform with the PROP definitions. The first two points in Fig.5 are the smoothed values for October 1965 and April 1966, given by Scott[24]; the values earlier in 1965 were not used, because 13th-order resonance occurred in mid 1965 and produced a substantial decrease in inclination, of order 0.02°, as is apparent from Fig.3 of Ref.24. The values plotted in Fig.5 after mid 1966 are (a) circles with standard deviation bars, which record the individual values with standard deviations less than 0.005° (with two omitted), and (b) triangles, which are the weighted means of groups of values including (unplotted) values with higher standard deviations.

In fitting theoretical curves to the points in Fig.5, a break was made at 14th-order resonance (10 April 1967), where it appears that there was a small increase in inclination of about 0.003°. The changes in inclination at 14th-order resonance experienced by other satellites at comparable inclinations suggest that a maximum change of 0.004° might be expected for 1962βτ6, so a change of 0.003° is acceptable. The 15th-order resonance occurs on 4 January 1968 at the time of the last group of points; the changes in inclination at resonance were evaluated using the THROE computer program with $10^9\bar{C}_{15} = -10$ and $10^9\bar{S}_{15} = -1$, but the net change was found to be less than 0.001°, which is less than the error in the values, and has therefore been ignored.

In fitting theoretical curves to the values, the weighted means (triangles) have been given the same weight as the most accurate of the individual values. The curve between 1965 and early 1967 is not very well defined, and the rotation rate of 1.1rev/day has an estimated standard deviation of 0.15. The curve between April 1967 and January 1968 is better defined, and the value of Λ, 1.2, has an estimated standard deviation of 0.1. The first value applies at 270km and the second at 265km. The scale of local time at perigee shows that both are fairly well averaged over all local times.

3.8 1963-27A

This satellite was an Agena rocket in a near-circular orbit at inclination 82°. For satellites in near-circular orbits, with eccentricity less than 0.005, equation (1) gives

$$\frac{\Delta i}{\Delta T_d} = \frac{\Lambda \sin i}{6\sqrt{F}} \left\{ 1 + \tfrac{1}{2}c + O(c^3, 0.01) \right\} \tag{4}$$

since the $O(c^2)$ terms vanish when e is small. So, if Λ is constant, the values of inclination for a circular-orbit satellite, when plotted against orbital period, should lie on a straight line whose slope gives the value of Λ.

Fig.6 shows the US Navy values of inclination for 1963-27A between May 1968 and its decay in October 1969, after removal of lunisolar and zonal harmonic perturbations, and with one value omitted. The variation with orbital period is near-linear and a least-squares fitted straight line has a slope of 0.192 ± 0.005rad/day. For this satellite $c = 0.19$, so equation (4) gives $\Lambda = 1.05 \pm 0.03$. Inspection of Fig.6 suggests that the lower end-point of the line is uncertain by about 0.0015°, corresponding to an error of 0.05 in Λ. So, for consistency with our other error estimates, we increase the error in Λ to 0.05. The value of Λ thus obtained applies at some 'mean' height, which is rather difficult to define satisfactorily: we take it to be a height half-way between the centre of gravity of the points plotted and the arithmetic mean of the highest and lowest of the heights. This gives 390km as the mean height, and, although this may be regarded as having an uncertainty of about 20km, a change in height of this order corresponds to a change in Λ smaller than the uncertainty in Λ.

The new value of Λ for 1963-27A ($\Lambda = 1.05 \pm 0.05$) differs substantially from the value previously[6] derived ($\Lambda = 1.17 \pm 0.1$), because the removal of lunisolar perturbations had a surprisingly strong effect on the slope of the fitted line.

3.9 Cosmos 54 rocket, 1965-11D

This satellite was the final-stage rocket used to launch Cosmos 54, 55 and 56 on 21 February 1965, and it remained in orbit for nearly five years at an inclination of 56°. We determined the orbit at 75 epochs from over 4000 observations[27]: the 34 orbits for which Hewitt camera observations were available proved very accurate, with typical standard deviations of 0.0005°. Previously, we divided the orbits into three groups and obtained three values of atmospheric rotation rate, all averaged over local time, as shown in Fig.5 of Ref.27.

In re-assessing the results, we decided that since the orbits were so accurate we ought to make a further division at the 29:2 resonance on 1 December 1968, where a perceptible glitch is visible on the graph. So, we now have four values of rotation rate. The first is from June 1966 to the 14th-order resonance in November 1967: the theoretical curve fits exceptionally well, but since the total change in inclination is so small, we have increased the previous standard deviation, taking $\Lambda = 1.10 \pm 0.15$. The second group of orbits, from March to November 1968, is well fitted[27] by $\Lambda = 1.00$, but we increase the standard deviation to 0.1, because the change in i is again very small. There was apparently a slight increase in inclination at the passage through the 29:2 resonance at the end of November 1968. Between December 1968 and the beginning of the 15th-order resonance in June 1969, $\Lambda = 1.1 \pm 0.1$. After the 15th-order resonance, from September to December 1969, we accept the previous value[27], but with an increased standard deviation, and take $\Lambda = 1.05 \pm 0.1$. All these values are averaged over local time, and the four values apply at heights of 305, 290, 280 and 245km respectively.

3.10 1965-11A, B and C and 1965-20A, B and C

These were two trios of nearly identical Cosmos satellites (Cosmos 54-56 and Cosmos 61-63) launched early in 1965, into orbits at 56° inclination with perigee heights near 260km, and apogee heights near 1700km. Their lifetimes ranged between 2.6 and 3.6 years, so they all independently sampled similar regions of the atmosphere at similar times. The orbits available are not of high accuracy, and the values of Λ previously obtained for the six satellites[4] were 1.2, 1.0, 1.2, 1.2, 1.2 and 1.1 respectively, all with estimated standard deviations of 0.2. Since the values are independent, it is legitimate to combine them into one value, namely, $\Lambda = 1.15 \pm 0.1$ at a height of 280km.

3.11 1966-118A

The satellite 1966-118A was an Agena rocket, like 1963-27A, in a circular orbit at 75° inclination. Fig.7 shows the values of inclination from US Navy orbits, after removal of perturbations, between May 1968 and its decay in April 1969. The values are plotted against orbital period, and a straight line fitted by least squares has a slope of 0.151 ± 0.007rad/day, giving $\Lambda = 0.86 \pm 0.04$ at an average height of about 410km. We increase the error to 0.1 after assessing the uncertainty at the end points.

3.12 Ariel 3, 1967-42A

Gooding[28] has determined 281 orbits of Ariel 3 from 10000 Minitrack observations, at three-day intervals between launch in May 1967 and August 1969, and his original analysis[5] of the inclinations has recently been repeated in greater depth[29], to determine the 15th-order resonance effect and atmospheric rotation rate. His result is $\Lambda = 0.77 \pm 0.05$ at a height near 530km.

3.13 1968-86A

This is another Agena rocket similar to 1966-118A, in a circular orbit at 75° inclination. Orbits were determined at 17 epochs from 950 observations by

Hiller[30], who plotted inclination (after removal of lunisolar and odd harmonic perturbations) against orbital period and fitted a straight line giving $\Lambda = 0.94 \pm 0.12$, for a height near 440km, as shown in Fig.2 of Ref.30.

3.14 Cosmos 316, 1969-108A

Cosmos 316 was launched on 23 December 1969 into an orbit of inclination 49.5^o, with a very low perigee height, near 150km, and apogee height 1640km. Because of its high mass/area ratio, Cosmos 316 remained in orbit for 8 months, and its orbit was determined at 36 epochs from 1600 radar, visual and photographic observations[31]. The average rotation rate over the lifetime was found to be 1.05 ± 0.05rev/day for a height of 160km. The orbits are accurate, and are worthy of more detailed analysis; but this requires consideration of the effects of meridional winds, and is deferred for subsequent study.

3.15 Cosmos 359 rocket, 1970-65D

This satellite was launched on 22 August 1970 into an orbit inclined at 51.2^o to the equator, with an initial perigee height of 209km: it decayed on 6 October 1971, and the orbit was determined at 42 epochs during the lifetime, using 2600 observations, including 89 from Hewitt cameras at Malvern and Edinburgh[32]. The mean value of rotation rate taken over the whole lifetime was 1.04 ± 0.05rev/day, for a height of 220km, but many of the orbits are extremely accurate, and a more detailed analysis would be appropriate. Again, however, the detailed study has been deferred because the role of meridional winds will have to be considered.

3.16 Ariel 4, 1971-109A

Ariel 4 was launched in December 1971 into a near-circular orbit of inclination 83^o at a height near 500km. Gooding[33] has determined orbits at 194 epochs from 16000 Minitrack observations, at dates between launch and December 1973, and has subsequently[29] analysed the changes in inclination over the first 171 epochs, to determine 15th-order resonance effects and the average atmospheric rotation rate. He finds $\Lambda = 0.81 \pm 0.04$ for a height of 520km.

3.17 Cosmos 472, 1972-04A

This satellite was launched on 25 January 1972 into an orbit with perigee height near 190km, and inclination 82^o; it decayed on 18 August 1972. The values of inclination from US Navy orbits from March to August, after removal of relevant perturbations, are plotted in Fig.8 with the theoretical curve for $\Lambda = 1.1$.

The orbit was carried rapidly through 15th-order resonance where the change in i should not exceed 0.003°; but, surprisingly, there appears to be a larger variation at the 29:2 resonance, and the fitting is therefore confined to dates after this resonance. Between the end of April and the beginning of August the curve fits well, and estimated rotation rate averaged over local time is 1.1 ± 0.1rev/day, for a height of 210km. (The earlier values of inclination change too little to give a realistic value of Λ.)

4 ORBITS WITH A BIAS IN LOCAL TIME

4.1 General

Satellites in orbits with eccentricities greater than 0.05 and perigee below 300km encounter appreciable air drag only over a limited arc of the orbit near perigee: 20° away from perigee the drag has usually fallen off to less than half its maximum value. For such orbits the atmospheric rotation exerts its influence primarily over this arc, extending 20° each side of perigee; so the satellite is effectively sampling the atmosphere over a span of local time centred on the local time at perigee, but extending each side of perigee, by up to ± 1 hour for a satellite in a medium-inclination orbit, or by a much smaller time, only a few minutes, for a near-polar orbit with perigee at low or middle latitudes.

The change in orbital inclination due to the effect of atmospheric rotation is usually too small to analyse over a time interval of less than a week, and sometimes the change must be allowed to build up for several months or even years (as shown by the satellites discussed in section 3) if a successful analysis is to be performed. However, the local time at perigee may change quite slowly: in Fig.8, for example, it changes by about 3 hours per week. If values of Λ could be obtained once a week, each value would cover only a few hours in local time. Another possibility is that the main decreases in inclination for a particular satellite, which occur when perigee is in low latitudes, may be at similar local times, so that the rotation rate obtained will be strongly biased towards those local times.

Preliminary work for this Report suggested that values of rotation rate biased towards the evening hours, approximately 18-24 hours local time, gave rather high rotation rates, and values biased towards the morning hours, approximately 04-12 hours local time, gave low rotation rates; so we have analysed the results on the basis of classifying the values in one of three categories: average; evening (18-24h); or morning (04-12h). Results for the individual satellites are described in sections 4.2 to 4.8.

4.2 ORS 2, 1966-51C

The Octahedron Research Satellite 2 was launched on 9 June 1966 into a polar orbit with perigee height 180km and apogee 3600km, and the inclination decreased by 0.16° during the 9-month lifetime. The local time at perigee changes by 12 hours whenever perigee passes the north or south pole, but only varies by 2 or 3 hours while the perigee is at latitudes less than 45°, where the main changes in inclination occur. So results for a short span of local time can be obtained by dividing the lifetime at each polar passage of perigee.

Fig.9 shows the values of orbital inclination, after removal of relevant perturbations: the triangles show the 20 orbits recently determined at RAE from Minitrack observations[34], which have an average standard deviation of 0.0015°. The other orbits (which are less accurate) are those determined in 1966-67 by NASA (circles), the US Navy (+ signs) and USAF (× signs). The orbits are well fitted by the theoretical curves, which give $\Lambda = 1.25 \pm 0.1$ for 18-21h on the first full section, $\Lambda = 0.80 \pm 0.06$ for 02-12h on the next two sections, and $\Lambda = 1.0 \pm 0.2$ during the decay phase (18-20h). The orbit passed rapidly through all the resonances marked, and the changes at resonance are unlikely to have exceeded 0.0025°. On the section with $\Lambda = 1.25$ the RAE orbits have standard deviations near 0.001°, so the possible change at resonance is the largest source of error, and sets the standard deviation of 0.1 quoted above. In the next two sections a slightly better fit can be achieved by splitting the $\Lambda = 0.8$ curve into three parts, with $\Lambda = 0.7$, 1.0 and 0.75, as shown by the broken lines. For our purposes, however, it is better to take the average through the two sections, with a possible error in inclination of 0.004°, made up of 0.003° from resonances, and 0.0025° from inaccuracy in the values. This estimated error of 0.004° on a total decrease of 0.054° gives a 7% error in Λ, leading to the value already quoted, $\Lambda = 0.80 \pm 0.06$. The value near decay is not accurate enough to be useful. In Fig.9 there are 149 values plotted: 20 values more than 0.008° from the curve have been omitted, but all the values in the last 9 days of the life are plotted.

4.3 OV1-15, 1968-59A

On 11 July 1968 the USAF launched this small and massive satellite into a polar orbit with perigee height 160km and apogee height 1800km. The satellite remained in orbit for 118 days, and orbits were determined at RAE[35] from the Baker-Nunn camera, radar and visual observations available, for 9 epochs. Satisfactory values of Λ were obtained from 1968-59A, but the orbits themselves do not come up to current standards of accuracy: so six of them have been redetermined with PROP6, to give improved values of inclination. The new standard deviations are about half the previous values.

Fig.10 shows the values of inclination, after removal of perturbations, given by these RAE orbits (circles), by US Navy orbits (+ signs), and by the means of groups of USAF Spacetrack values (× signs). The orbit of this satellite has also been analysed by Ching[36], but the 150 values of inclination shown in Fig.4 of her paper exhibit a considerable scatter, of about 0.02°. The accuracy appears to be much better, however, from 6 to 16 September, and from 26 September to 6 October. Values for these dates are included in Fig.10, after removal of lunisolar perturbations.

The local time at perigee jumps by 12 hours whenever perigee crosses the north or south pole, and there are three groups of local times: 10-11h, 18-21h and 4-5h. The observational values are well fitted by theoretical curves with $\Lambda = 0.9$, 1.2 and 1.1 on the three sections. The first of these values of Λ is for morning hours and conforms to the expected pattern by being less than 1.0; but the estimated error is 0.3, so the value has to be discarded. The other two values are quite acceptable, and give $\Lambda = 1.2 \pm 0.1$ at 175km height for 18-21h local time, and $\Lambda = 1.1 \pm 0.1$ at 165km for local time 4-5h. This local time of 4-5h is unfortunate because it falls between our 'morning' and 'average' categories: we have (arbitrarily) chosen to plot it as an 'average' value.

The newly computed orbits obtained are recorded in Table 2 (page 29).

4.4 Cosmos 268 rocket, 1969-20B

The orbit of Cosmos 268 rocket, with inclination 48.4° and perigee height near 220km, has been determined at RAE at 28 epochs during its 342-day life, from 1500 observations, including 44 accurate photographic observations[37]. Local time at perigee varies only slowly, taking 270 days to progress through 24 hours, and a separation in local time is possible. The values obtained are:

$\Lambda = 0.8 \pm 0.1$ for 04-14h (April-July 1969) at height 250km
$\Lambda = 1.3 \pm 0.15$ for 19-03h (July-October 1969) at height 245km
$\Lambda = 0.8 \pm 0.2$ for 10-19h (October 1969-February 1970) at height 230km.

These values are similar to those previously given, but there are small changes as a result of allowing for 14th and 15th-order resonances. We discard the third value as of inadequate accuracy, but it may be possible to obtain a better value after the 15th-order resonance has been analysed in detail.

4.5 Cosmos 307 rocket, 1969-94B

The orbit of 1969-94B was determined by Hiller at 25 epochs during its 9-month life, from 1200 observations[38]. This was another satellite with inclination near 48° and perigee height near 200km, and with a slow variation in local time at perigee. A single value of Λ did not fit well, and in our revised analysis, Fig.11, we have made two breaks, at the time of 14th-order resonance (20 March 1970) and at the end of May 1970. Between November 1969 and March 1970, $\Lambda = 1.0$ fits the points well, but with a rather large standard deviation, 0.15, because the decrease in inclination is small: the local time at perigee is 5-13h and the height 240km. Between March and May 1970, $\Lambda = 1.3$ fits well, but at the end of May there appears to be a discontinuity in i, indicated by the broken line, possibly connected with the rapid increase in spin rate reported at this time[38]. We therefore ignore the five values after the beginning of June 1970 and take $\Lambda = 1.3 \pm 0.1$ for March-May 1970, local time 20-03h, height 235km.

4.6 Cosmos 347 rocket, 1970-43B

The orbit of 1970-43B was determined by Hiller[39] at 23 epochs during its 8-month life, using 850 observations, including 37 from the Malvern and Edinburgh Hewitt cameras. The perigee height was near 220km, and the inclination near 48°, as with the two previous satellites. So again values for specific local times can be obtained. We divided the orbits into two groups, from launch to 14th-order resonance (July-October 1970), and between 14th and 15th-order resonance (November 1970-January 1971). The two values of Λ derived are both 1.3 ± 0.1, but there is some doubt about the first value, because the satellite's spin period decreased rapidly during September, presumably as a result of unused propellant escaping. While this spin-up was in progress, the perigee height showed[39] an unexpected decrease of several km, and it is likely that the inclination was also affected. So we use only the second value of rotation rate, $\Lambda = 1.3 \pm 0.1$ for a height of 230km and local time 18-01h.

4.7 Cosmos 378 rocket, 1970-97B

Launched on 17 November 1970 into an orbit with perigee height 230km and inclination near 74°, 1970-97B remained in orbit until 30 September 1972.

Its orbit was determined by Hiller[40] at 39 epochs from more than 1900 observations, including 89 Hewitt camera observations. Two good values of Λ were obtained, 0.75 ± 0.05, between 14th and 15th-order resonance, and 1.0 ± 0.1 after 15th-order resonance. The second of these values is averaged over local time. The first value of Λ, 0.75 ± 0.05, which applies between June 1971 and May 1972, runs through four cycles in local time, and might also be expected to be averaged in local time. However, the decrease in inclination due to a rotating atmosphere is steepest when perigee is near the equator, at latitudes less than about 30°, and it so happens that the three steep decreases in inclination occur at local times which are heavily biased towards the range 6-14h. This is because perigee travels relative to the Sun at approximately twice its average rate of travel round the orbit: hence the local time at perigee changes by about 24 hours (360°) as the perigee progresses 180° from one equator crossing to the next[40].

4.8 Cosmos 408 rocket, 1971-37B

This satellite was launched on 24 April 1971 and entered an orbit with an initial period of 101.9 minutes, and an inclination of 81.8°. The initial perigee height was 200km, and the lifetime 158 days. Fig.12 shows the values of inclination from the weekly US Navy orbits from mid-May until decay, cleared of relevant perturbations. The change in inclination on passing through 15th-order resonance was calculated to be -0.003°, using the THROE computer program with pre-assigned values for the lumped harmonics ($10^9\bar{C}_{15} = -26$, $10^9\bar{S}_{15} = -9$). The values of inclination are well fitted by two separate theoretical curves, $\Lambda = 0.6 \pm 0.2$ before the resonance, where the decrease is very small, and $\Lambda = 1.3 \pm 0.1$ after the resonance, for 16-23h local time, and a height of 220km. The first value is of inadequate accuracy, but the second is quite satisfactory, although based on sparse data. The value should, however, be regarded as provisional, because the orbit of 1971-37B is now being determined from photographic, visual and radar observations at the University of Aston, to improve upon these results.

5 ANALYSIS OF THE VARIATIONS IN Λ

5.1 Conspectus of results

The individual values of Λ reported in sections 3.2-3.17 and in sections 4.2-4.8 are brought together, in the same order, in Table 1. The successive columns of Table 1 give first the satellite and the value(s) of Λ; then the corresponding height, local time (either specifically or just as 'average'), inclination of the orbit and average solar activity, as expressed by the 10.7cm radiation energy ($S_{10.7}$).

Table 1

VALUES OF Λ OBTAINED FROM THE ORBITS ANALYSED, WITH CORRESPONDING VALUES OF HEIGHT, LOCAL TIME, INCLINATION AND SOLAR ACTIVITY (10.7cm RADIATION ENERGY)

Satellite		Λ	Height km	Local time hours	Inclination deg	$S_{10.7}$ $10^{-22} W m^{-2} Hz^{-1}$
1958α	Explorer 1	1.5 ± 0.1	400	Average	33	200
		1.2 ± 0.1	380	"	33	100
		1.3 ± 0.1	355	"	33	150
1960γ2	Transit 1B	1.3 ± 0.1	360	"	51	90
1962ο1	Ariel 1	1.1 ± 0.15	420	"	54	110
		1.1 ± 0.1	400	"	54	130
1962βτ1 and 1962βτ5		1.30 ± 0.10	250	"	70	90
1962βτ2	Injun 3	1.3 ± 0.1	260	"	70	90
		1.2 ± 0.1	255	"	70	150
1962βτ6	Injun 3 rocket	1.1 ± 0.15	270	"	70	100
		1.2 ± 0.1	265	"	70	130
1963-27A		1.05 ± 0.05	390	"	82	150
1965-11D	Cosmos 54 rocket	1.1 ± 0.15	305	"	56	120
		1.0 ± 0.1	290	"	56	140
		1.1 ± 0.1	280	"	56	150
		1.05 ± 0.1	245	"	56	150
1965-11A,B&C and 1965-20A,B&C		1.15 ± 0.1	280	"	56	130
1966-118A		0.86 ± 0.1	410	"	75	150
1967-42A	Ariel 3	0.77 ± 0.05	530	"	80	150
1968-86A		0.94 ± 0.12	440	"	75	150
1969-108A	Cosmos 316	1.05 ± 0.05	160	"	49	160
1970-65D	Cosmos 359 rocket	1.04 ± 0.05	220	"	51	150
1971-109A	Ariel 4	0.81 ± 0.04	520	"	83	110
1972-04A	Cosmos 472	1.1 ± 0.1	210	"	82	120

Satellite		Λ	Height km	Local time hours	Inclination deg	$S_{10.7}$ $10^{-22} W m^{-2} Hz^{-1}$
1966-51C	ORS 2	1.25 ± 0.1	210	18-21	90	120
		0.80 ± 0.06	210	02-12	90	120
1968-59A	OV1-15	1.2 ± 0.1	170	18-21	90	140
		1.1 ± 0.1	165	Average	90	150
1969-20B	Cosmos 268 rocket	0.8 ± 0.1	250	04-14	48	150
		1.3 ± 0.15	245	19-03	48	140
1969-94B	Cosmos 307 rocket	1.0 ± 0.15	240	05-13	48	160
		1.3 ± 0.1	235	20-03	48	160
1970-43B	Cosmos 347 rocket	1.3 ± 0.1	230	18-01	48	155
1970-97B	Cosmos 378 rocket	0.75 ± 0.05	250	06-14	74	120
		1.0 ± 0.1	230	Average	74	120
1971-37B	Cosmos 408 rocket	1.3 ± 0.1	220	16-23	82	110
- - -	- - -	- - -	- - -	- - -	- - -	- - -
1964-76A	Blum and Schuchardt (Ref.7)	0.73 ± 0.14	580	11	81	130
		1.11 ± 0.14	580	22	81	130
		0.92 ± 0.10	580	Average	81	130
1967-64A	Forbes (Ref.9)	0.90 ± 0.1	155	11	111	120
1968-31A		0.85 ± 0.2	155	10	111	130
1961δ1	Slowey (Ref.8)	1.41 ± 0.14	355	20-22	39	80
1963-30D		0.79 ± 0.11	360	06-08	85	150
1964-4A		0.78 ± 0.07	675	06-08	81	150

At the end of the table the results obtained by Blum and Schuchardt[7], by Forbes[9] and by Slowey[8] are listed in the form in which we plot them. Blum and Schuchardt have analysed the orbit of the balloon satellite 1964-76A over a number of years at heights averaging 580km, and have found a day-to-night variation for which a fitted curve gives a maximum Λ of 1.11 at 22h local time, and a minimum of 0.73 at 11h local time, with average 0.92. Forbes has obtained several values for short-lived satellites at heights near 155km, but most of them are during strong geomagnetic disturbances, and only two are suitable for inclusion here, for 10 and 11h local time. Slowey has analysed the orbits of several balloon satellites, of which three give results suitable for inclusion, 1961δ1 at 20-22h local time, and 1963-30D and 1964-04A at 6-8h; the heights are 355, 360 and 675km respectively. These additional results are very helpful in establishing the variation of Λ with height.

5.2 Variation of wind speed with height and local time

Fig.13 shows the values of Λ recorded in Table 1, plotted against height for three categories of local time: evening (18-24h); morning (4-12h); and average. The evening values we have obtained are indicated by upward-pointing triangles, the morning values by downward-pointing triangles, and the average values by black circles, all with unbroken 'error bars'. The values from other sources have upward or downward pointing arrows, rather than triangles, and have their error bars shown as broken lines. It is obvious from Table 1 that not all the values which are biased in local time fit exactly into the 'evening' or 'morning' category: some fall between 'average' and either 'evening' or 'morning'. But we decided to ignore these fine distinctions and to place each point in the most appropriate of the three divisions.

In Fig.13 three curves have been drawn through the points to give an impression of the variation of wind speed with height for the three categories of local time. The solid curve, through the points averaged over local time, shows that the rotation rate (in rev/day) increases from near 1.0 at 150km to 1.3 near 350km (corresponding to an average west-to-east wind of 120m/s), and then declines to 1.0 at 400km, and probably to about 0.8 at greater heights. The upper broken curve shows that in the evening the wind is from west to east, increasing from about 50m/s at 150km height, to a maximum of about 150m/s near 350km; above that the data are sparse, but a decline to near zero by 600km seems probable. The lower broken curve shows consistent east-to-west winds in the morning, of magnitude 50-100m/s above 200km.

It should be emphasized that these results refer to winds averaged over all conditions of solar activity and geomagnetic disturbance. The winds are sampled at latitudes from 0 to 55°, but with a bias towards the lower latitudes. The day-to-day behaviour of the atmosphere may vary widely from these norms: it is the strength - and the weakness - of the satellite orbit analysis that it gives an impression of the *average* atmosphere.

We have ignored the value $\Lambda = 1.5$ from Explorer 1 in drawing the curves in Fig.13. This omission is from necessity rather than choice; but the neglect of this value is not unreasonable, since it applies for a level of solar activity far higher than prevails for any of the other values (as Table 1 shows), and is also for a lower latitude.

The new values for average rotation rate are somewhat lower than in our previous papers, because most of the high values of Λ have been removed into the 'evening' category, and the high value from Explorer 1 has been ignored.

5.3 Influence of geomagnetic disturbances, solar activity and latitude

It is well known that upper-atmosphere winds are usually enhanced at times of geomagnetic disturbance, when the influx of particles as a result of disturbances in the solar wind causes heating in the auroral zones, which spreads its influence equatorwards. During geomagnetic storms, winds in the auroral zones of up to 500m/s have been measured by Rees[41], using vapour-trail methods, and by Brekke, Doupnik and Banks[42], from radar back-scatter techniques; winds of up to 1000m/s have been recorded by Feess[43], with accelerometers on a satellite; while Forbes[9] has measured winds of up to 350m/s, using satellite orbit analysis. These are short-term effects lasting for a few days at most, like the geomagnetic disturbance itself. Our analysis here is long-term, however; so we have not attempted to assess the correlations between geomagnetic disturbances and upper-atmosphere winds.

The average values of Λ in Fig.13 have been plotted against the solar activity index, $S_{10.7}$, in Fig.14a. There is a slight tendency for Λ to decrease as $S_{10.7}$ increases from 80 to 150 units, and to increase again for higher activity, if the $\Lambda = 1.5$ point from Explorer 1 is accepted. Opinions will differ on the significance of the variation: the scatter near $S_{10.7} = 150$ is considerable, but the tendency for high rotation rates at low solar activity is fairly clear, and is supported by Slowey's evening value[8] of $\Lambda = 1.41$ for $S_{10.7} = 80$.

In Fig.14b the average values of Λ are plotted against the latitude ϕ defined in section 2.1, the maximum latitude up to which the zonal winds are effective in altering the inclination. Fig.14b gives the impression that Λ may be higher near the equator, but this conclusion is a little doubtful, because the five lowest values at $\phi > 50^{\circ}$ are for heights above 400km, where all the values of Λ are lower.

To resolve this doubt, the average values of Λ have been replotted against height in Fig.15, as circles if the orbital inclination is less than 60°, or as diamonds for inclinations greater than 60°. At heights above 350km, the higher-inclination satellites do give lower values of Λ, and two curves have been drawn in Fig.15 to illustrate this division. The possibility of such a division was mentioned[6] in 1972, and most of the recent theoretical studies indicate greater average west-to-east winds near the equator. However, Fig.15 shows no sign of such an effect at heights below 300km: there the near-polar orbits seem to give slightly higher values of Λ. The splitting of the curve in Fig.15 looks quite convincing, but the division must be regarded as tentative until more results are available.

6 MERIDIONAL WINDS

We make no attempt here to assess meridional winds. It is possible that some of the satellites analysed may yield information about meridional winds, particularly 1969-108A and 1970-65D, but these studies are deferred.

There are other orbits which may be analysed to determine meridional winds. Orbits with inclinations near 63° and $\cos \omega$ near 0.1 are particularly suitable, because they are much more sensitive to meridional than to zonal winds. A good example is 1970-114F, from which meridional winds at a height near 110km were recently evaluated[44], and shown to be enhanced on geomagnetically disturbed days.

7 COMPARISONS WITH THEORETICAL MODELS

In the past few years numerous theoretical papers have been published in which zonal wind patterns are derived under various simplifying assumptions. The results of these studies do not agree too well in detail, but there are some broad features which figure in most of the results.

Nearly all the recent theoretical analyses indicate that at heights above 200km an approximately sinusoidal variation of wind speed occurs during each day, the maximum west-to-east velocity being at a local time between 18 and 24h, and the maximum east-to-west velocity at a local time between 03 and 12h. Typical maximum wind speeds are 100-200m/s, but computations of the average west-to-east wind over all local times show wide variations: some of the papers give values as high as 50-100m/s, but in many the average value is virtually zero, and in some it is slightly negative.

We now give examples from some of the most relevant recent papers, with U as the west-to-east wind velocity, and $\bar{U}$ as the average value of U :

(1) For equatorial conditions and heights near 240km, Heelis, Kendall, Moffett, Windle and Rishbeth[45] find $U = -80$m/s at 08h, $U = 0$ at 18h, $U = 230$m/s at 23h and $U = 0$ again at 06h, with $\bar{U} = 55$m/s . This last value corresponds to $\Lambda = 1.11$, in good agreement with Fig.13.

(2) Blum and Harris[46] obtain values of Λ between 1.10 and 1.15 for heights between 240 and 340km and latitudes of 0-30°, in fairly good agreement with our results; but they see no mechanism for producing a decrease in Λ as height increases above 350km. We have not yet been able to make a satisfactory test of their suggestion that Λ is larger at solstice than at equinox.

(3) Amayenc, Alcayde and Kockarts[47] study winds at middle latitudes and 300km height, and find that U ranges from -180m/s at 05h to 120m/s at 21h, the mean value being slightly negative, in disagreement with our results.

(4) Straus, Creekmore, Harris, Ching and Chiu[48] obtain the variation of wind speed at 400km height for three latitudes, 18°, 37° and 65°. For 18° latitude, U ranges between -130m/s at 08h and 70m/s at 20h, with a small mean value.

(5) Straus and Schulz[49] have extended the preceding work to take account of magnetospheric electric fields, but the times of the maxima and the value of $\bar{U}$ are not much altered.

(6) Izakov, Morozov and Yashchenko[50] have derived zonal winds in the equatorial regions at equinox. At heights near 150km the extremes of U are -10m/s at about 11h local time, and +100m/s at about 23h. For a height of 320km the extremes are -30m/s at 08h and +300m/s at 22h, with a mean value of about 100m/s ($\Lambda = 1.2$, in approximate agreement with Fig.13).

(7) Roble[51] has given the variation of zonal wind for heights of 120-500km over Millstone Hill (latitude 42.6° north) on 23-24 March 1970; as calculated from incoherent scatter radar measurements and an ionospheric

model. At a height of 200km U has extremes of -150m/s at 05h and +150m/s at 21h. The value of $\bar{U}$ appears to be slightly negative.

(8) Antoniadis[52] has given similar results for four dates (including Roble's). The winds are east-to-west between 03 and 12h, with maximum speeds between 100 and 250m/s; and west-to-east between 16 and 24h, with maximum speeds between 100 and 350m/s. The average zonal wind varies considerably for the four dates, between 'weak and westward' and 'strong and eastward'.

(9) Blum and Harris in a later paper[53] give wind patterns for 300km height at solstice and equinox. The zonal winds are west-to-east from 16 to 24h, and east-to-west, but slightly less strong, from 04 to 12h, and stronger at solstice than equinox. Near the equator the mean west-to-east wind is about +30m/s at 200-250km at equinox (Λ = 1.07); presumably it is higher at solstice, but figures are not given.

The theoretical background of super-rotation has been reviewed by Rishbeth and Dickinson[54,55]; but their reviews were published before any of the papers discussed above.

8 OTHER MEASUREMENTS OF ZONAL WINDS

Zonal winds have also been measured by determining the drift velocity of trails of vapour released from high-altitude rockets; by accelerometers and other instruments aboard satellites; by measuring Doppler shifts in emission lines of the airglow; and less directly by interpreting ion movements, particularly from radar backscatter measurements. To review these results in detail would be a lengthy task, which we do not attempt here.

The vapour trail method is excellent, but expensive, because each firing gives a wind measurement at only one location and one local time: the total number of measurements above 200km is even now not enough to give a global picture. Neal[56] has reviewed results from vapour trail measurements: for heights greater than 200km, these are mainly at latitudes >25°N. His review indicates that in general there are west-to-east winds from 17h through midnight to 02h, and east-to-west winds from 05h to 12h, though the wind speeds vary widely.

The radar backscatter method is powerful, but it is (a) confined to one location, (b) requires expensive equipment, and (c) is dependent on a correct theory for determining neutral atmospheric motions from the measured ion motions. Excellent results can be obtained however, as shown for example by the results of Antoniadis[52] quoted in section 7, and, as the theories improve, this method will gain more momentum.

Using accelerometers or other instruments aboard satellites is another powerful method, but at the expense of a satellite launching. With the Doppler measurement of airglow lines, there are difficulties in deciding the height at which the measurement applies. Other ionospheric measurements that may give wind speeds have been reviewed by Kent[57].

All these methods can give results confined to within a few minutes in local time. Analysis of satellite orbits, on the other hand, very rarely allows a determination to closer than one hour in local time, and sometimes the results are averaged over all local times, as we have seen. This automatic averaging is beyond the scope of the other methods, unless many thousand measurements were made from different places.

Measurements of zonal wind speeds by analysis of satellite orbits have been made by a number of authors, but most of these determinations do not quite come up to the standards which we have set for our results in this paper, either because the orbital data are not accurate enough, or because the variations at 14th and 15th-order resonance have not been taken into account. In Fig.13 we have already used results from three papers where resonance effects are not likely to be significant. Several of the values of Λ obtained by other authors have standard deviations which appear to be lower than ours: but these are statistical standard deviations rather than attempts at a real estimate of the error, as in our values. We should have liked to use the results obtained by Sehnal[58], who found values of Λ of 1.20, 1.25 and 1.10, with nominal standard deviation 0.05, from Intercosmos 3, 5 and 9 at heights of 220, 215 and 210km respectively. However, Sehnal states that the original values of the elements he used 'showed great scatter' and even the smoothed values were not considered accurate enough for lunisolar, odd harmonic or resonance corrections to be worth applying. So we did not use these results, although they would fit well in Fig.13: the estimated errors in Schnal's three values, using our methods, would be 0.13, 0.2 and 0.2 respectively. From analysis of 1966-92D, Bowman[59] obtained $\Lambda = 1.1 \pm 0.1$ at 140km height for 13-19h local time; but on the basis of his data, we would assess his likely error as 0.2 rather than 0.1.

9 CONCLUSIONS

After critically reviewing previous analyses of satellite orbits for determination of zonal winds, and rejecting the less accurate results, we are left with 44 values (36 of ours and 8 from other papers), which are plotted in Fig.13, to show the variation of zonal wind speed with height between 150 and

700km. It is fruitful to divide the points into three categories of local time: morning (4-12h); evening (18-24h); and average. Fig.13 shows that the rotation rate Λ (in rev/day) averaged over all local times increases from near 1.0 at 150km to 1.3 near 350km, corresponding to an average west-to-east wind of 120m/s at this height. Above 350km the average rotation rate decreases, to 1.0 at 400km, and probably to about 0.8 at greater heights, although there are only three values above 500km, all from polar orbits. The maximum west-to-east winds occur in the evening (18-24h), and have a maximum strength of about 150m/s at heights near 350km, decreasing to near zero around 600km. The morning winds (4-12h) are from east to west, with speeds of 50-100m/s above 200km. There are only 8 evening and 9 morning values, so the morning and evening winds are less accurately determined, and subject to ±50m/s error.

These results represent an average over all levels of solar activity and geomagnetic disturbance. The winds are sampled at latitudes up to about 55°, though with a bias towards the range 0-30°. The day-to-day behaviour of the atmosphere may vary widely from these norms: for example, it is well-known that wind speeds are generally enhanced at the times of geomagnetic storms.

The variation of the average values of Λ with solar activity and latitude is shown in Figs.14 and 15. We may tentatively conclude, from Fig.14a, that the value of Λ tends to be high when solar activity is low; and, from Fig.15, that at heights above 350km Λ is larger in near-equatorial latitudes (0-25°) than at higher latitudes (25-50°).

Our separation of the Λ values into three groups dependent on local time may seem only a small advance. But we regard it as a considerable step forward, because it provides a much better framework for interpreting future results, and identifying other variations in Λ. Results from a number of other satellites should soon become available.

Acknowledgments

We thank H. Hiller and R.H. Gooding, whose orbit analyses have contributed to this Report.

Table 2

THE SIX SETS OF REVISED ORBITAL PARAMETERS FOR 1968-59A, WITH STANDARD DEVIATIONS

MJD	Date 1968	a	e	i	Ω	ω	M_0	M_1	M_2	M_3	M_4	M_5	ε	N	D
40056.0	Jul 19.0	7337.524	0.10999	89.8737	280.290	175.37	301.05	4974.135	2.233	0.0277	-0.0006	-0.0011	0.25	40	5.9
		1	8	35	3	3	4	2	1	7	1	1			
40067.0	Jul 30.0	7284.320	0.10513	89.8660	280.139	140.84	233.76	5028.750	2.306	-0.0127	0.0045	-	0.42	15	7.2
		4	28	45	4	3	3	4	1	4	1				
40089.0	Aug 21.0	7188.224	0.09300	89.8600	279.789	69.82	36.24	5129.965	2.366	0.0021	-	-	1.52	14	5.8
		3	4	27	4	4	4	3	2	6					
40112.0	Sep 13.0	7053.757	0.07483	89.8282	279.336	352.06	6.70	5277.409	4.336	-0.0503	-0.0709	0.0168	0.77	26	4.0
		9	4	19	1	2	2	10	13	54	70	20			
40126.0	Sep 27.0	6981.685	0.06447	89.8161	279.028	300.81	19.88	5359.372	2.000	-0.0176	-0.0019	-	0.68	28	5.3
		2	2	21	2	2	2	2	3	4	4				
40141.0	Oct 12.0	6932.643	0.05808	89.8122	278.667	243.92	197.18	5416.365	2.200	0.1422	0.0358	-	0.86	21	3.8
		4	2	30	2	3	3	5	6	23	17				

Key: MJD = modified Julian day

a = semi major axis (km)

e = eccentricity

i = inclination (deg)

Ω = right ascension of ascending node (deg)

ω = argument of perigee (deg)

M_0 = mean anomaly at epoch (deg)

M_1 = mean motion n (deg/day)

M_2 = $\frac{1}{2}\dot{n}$ (deg/day^2)

M_3, M_4, M_5 later coefficients in the polynomial for M

ε = measure of fit

N = number of observations used

D = time covered by the observations (days)

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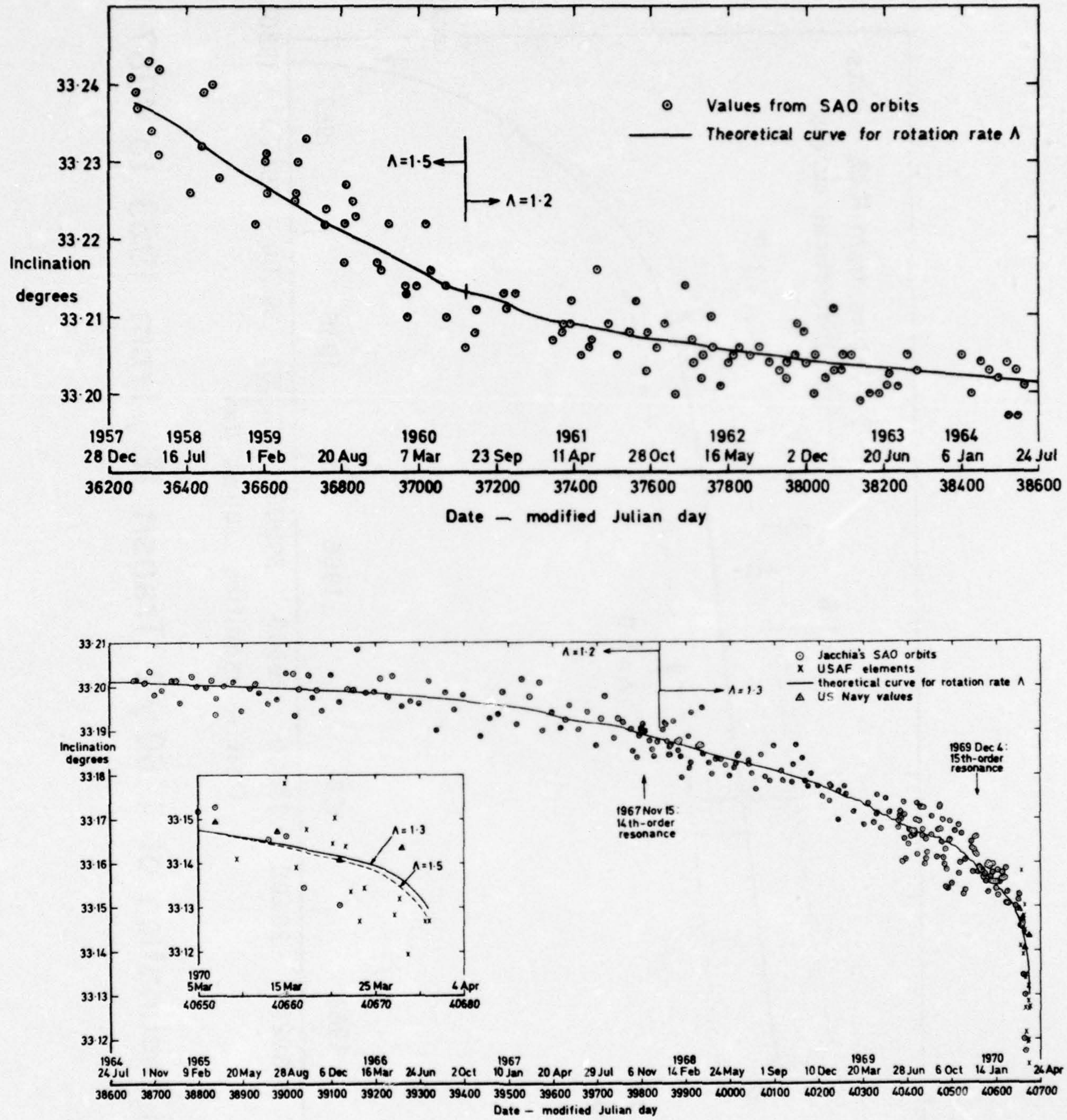

Fig.1 Orbital inclination of Explorer 1, 1958α, from 1958 to 1970

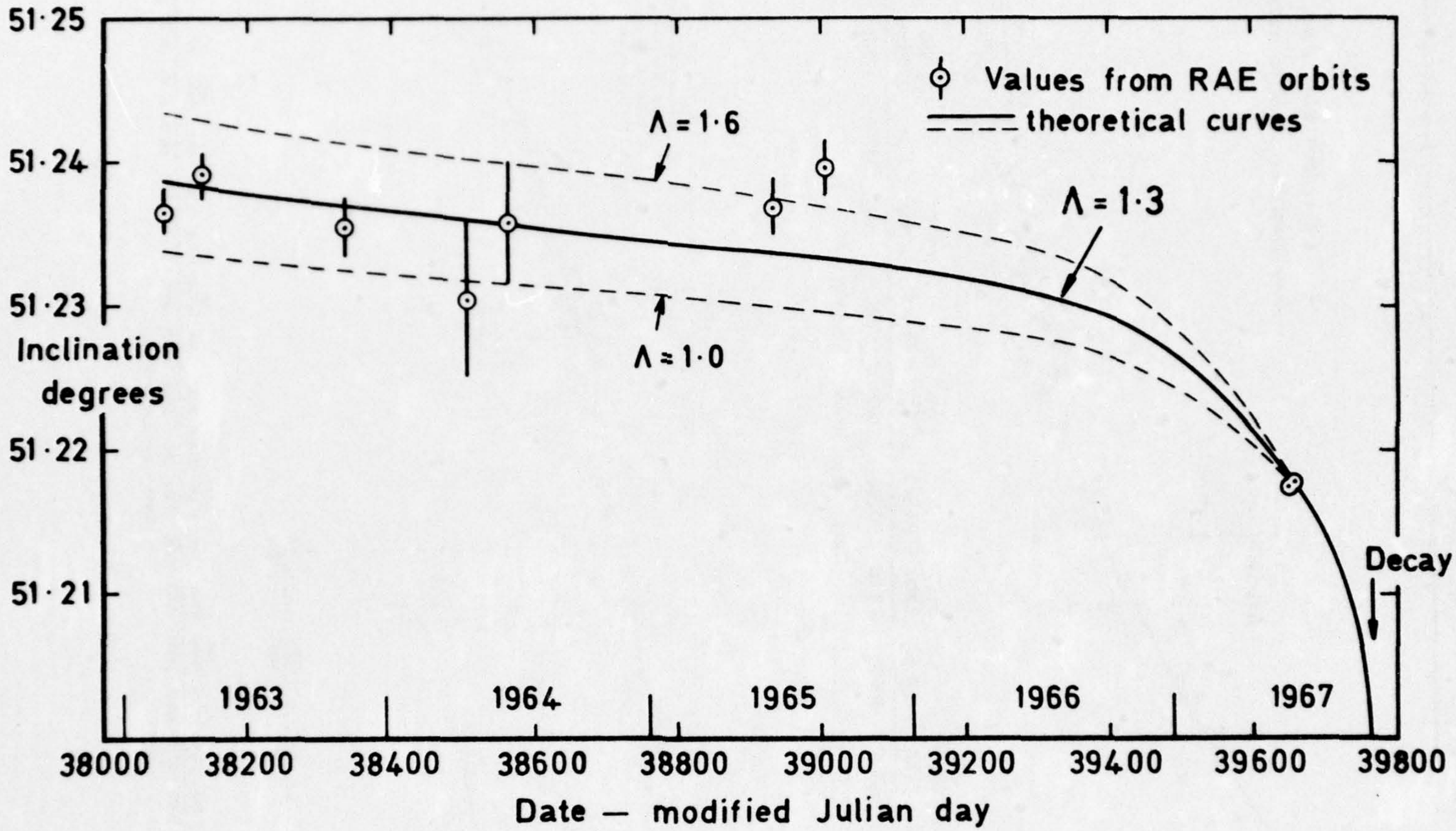

Fig. 2 Orbital inclination of 1960 γ 2, Transit 1B, from 1963 to 1967

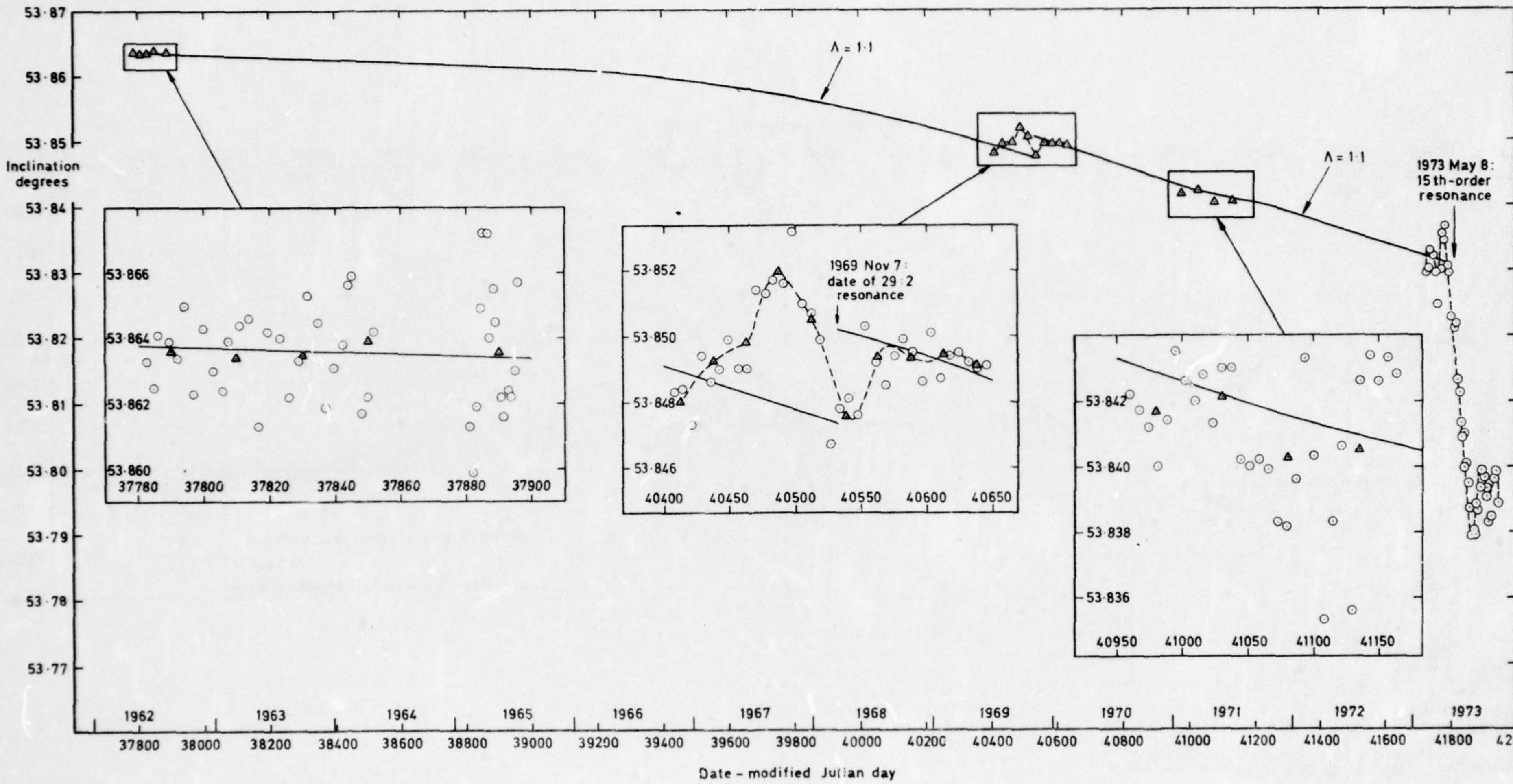

Fig.3 Orbital inclination of 1962o1, Ariel 1, from April 1962 to September 1973

Fig.3

Fig.4

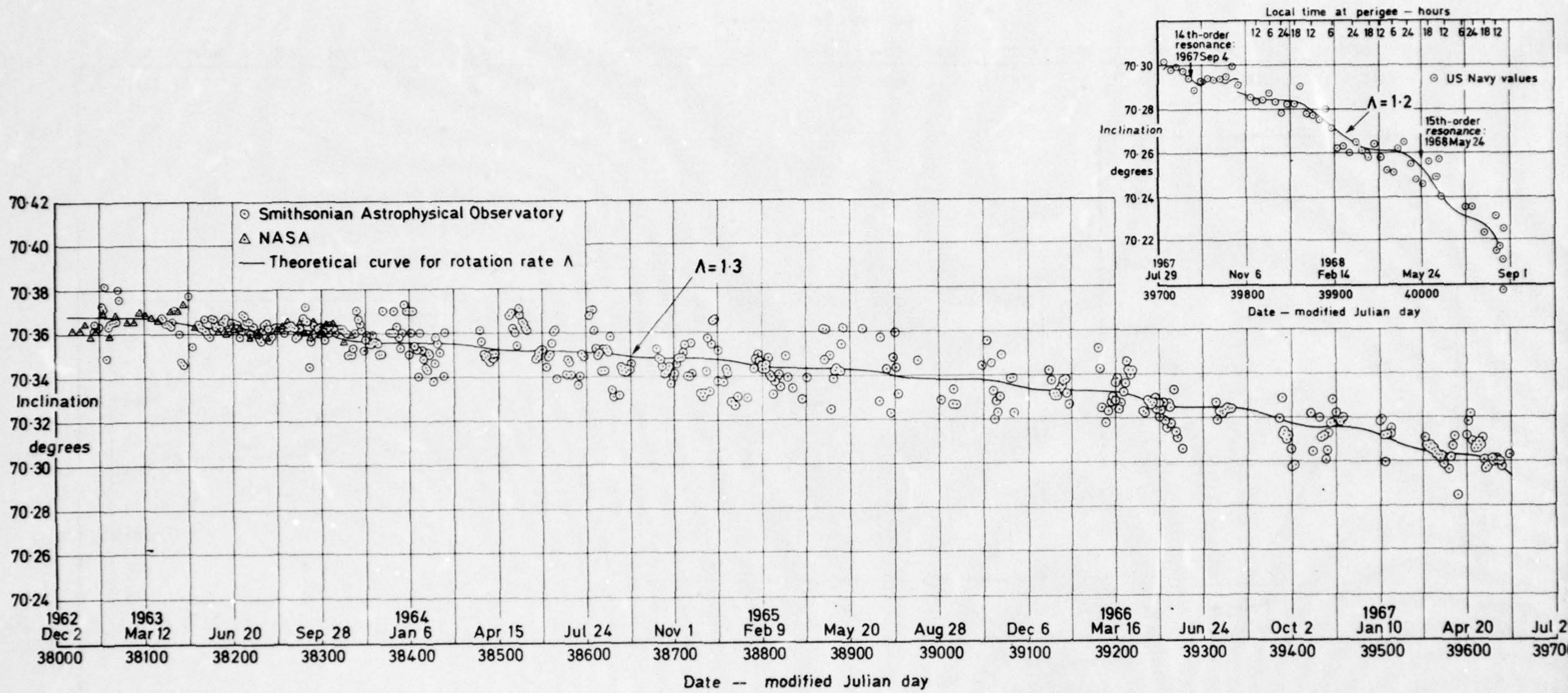

Fig. 4 Orbital inclination of 1962 $\beta\tau$2, Injun 3, from Dec 1962 to Aug 1968

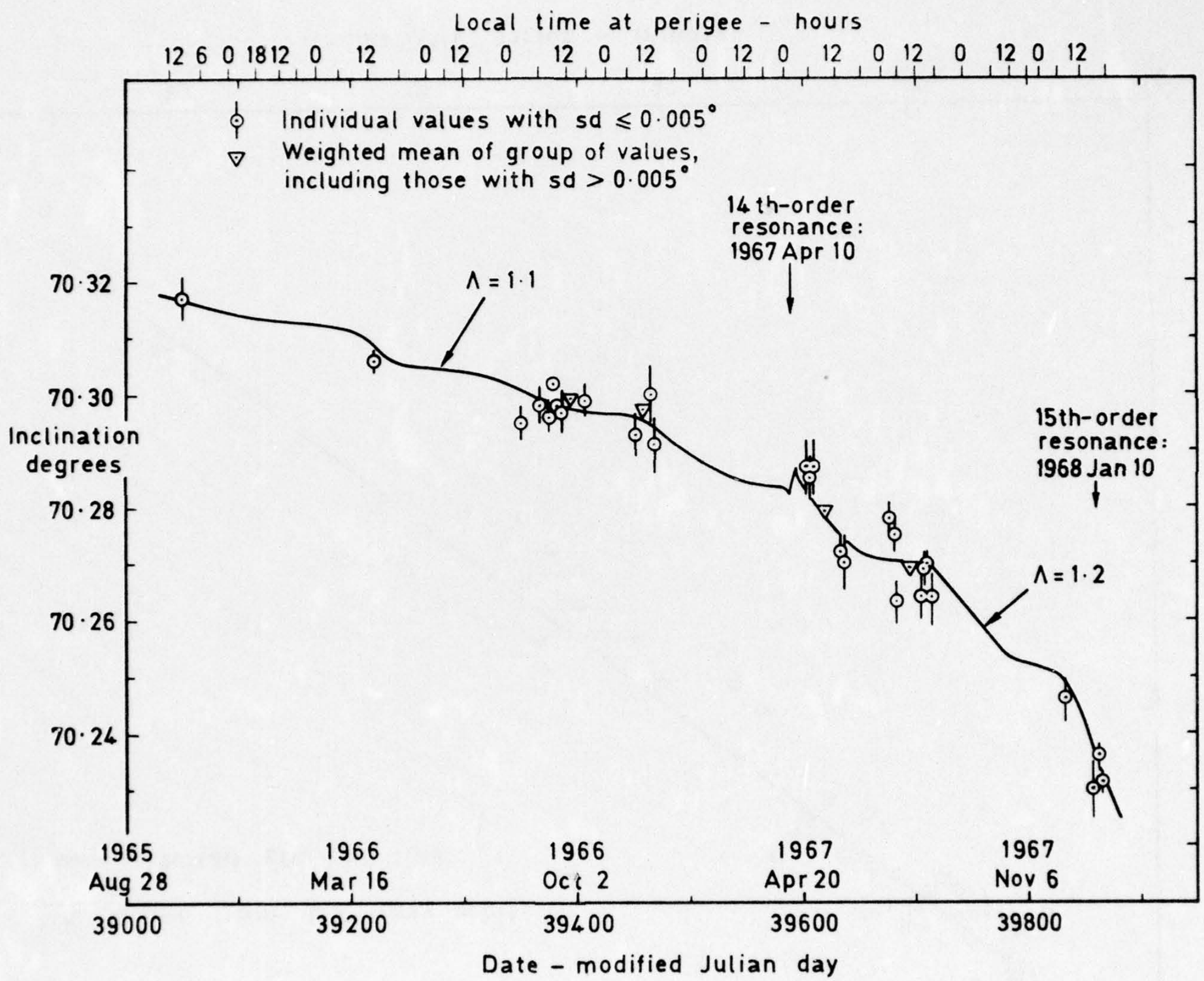

Fig.5 Orbital inclination of 1962 $\beta\tau$ 6, Injun 3 rocket, from October 1965 to January 1968

Fig. 6

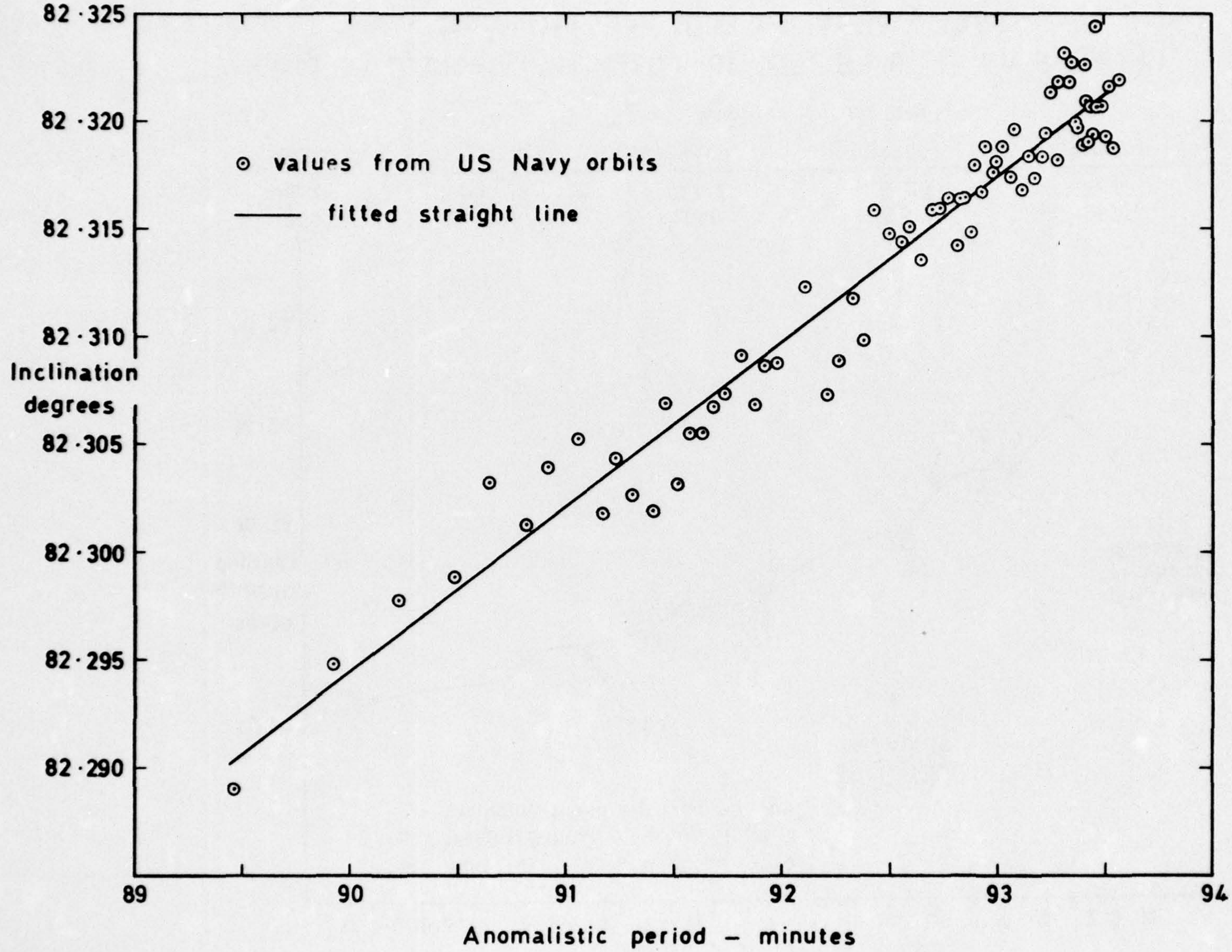

Fig. 6 Inclination versus orbital period for 1963–27A

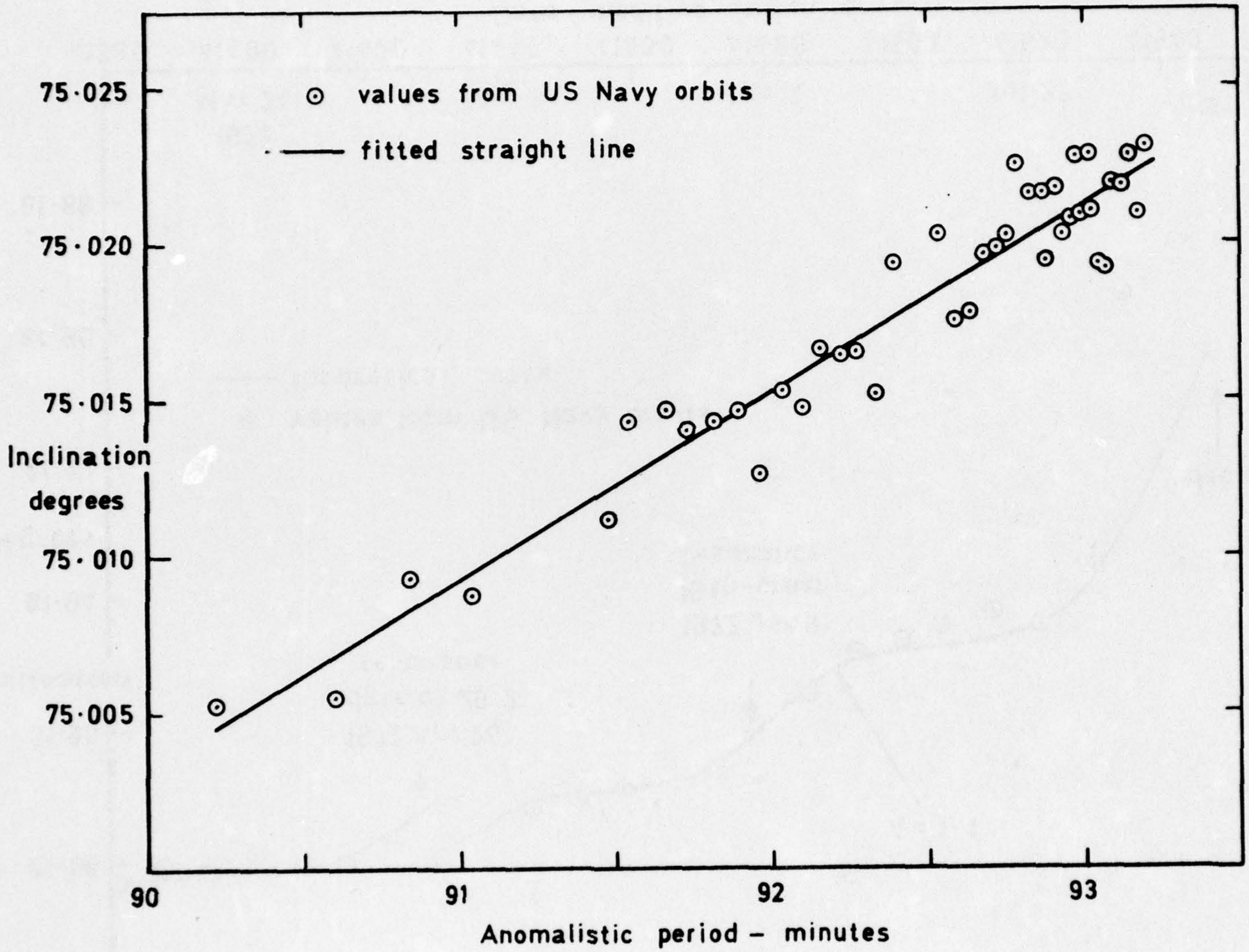

Fig. 7 Inclination versus orbital period for 1966 – 118A

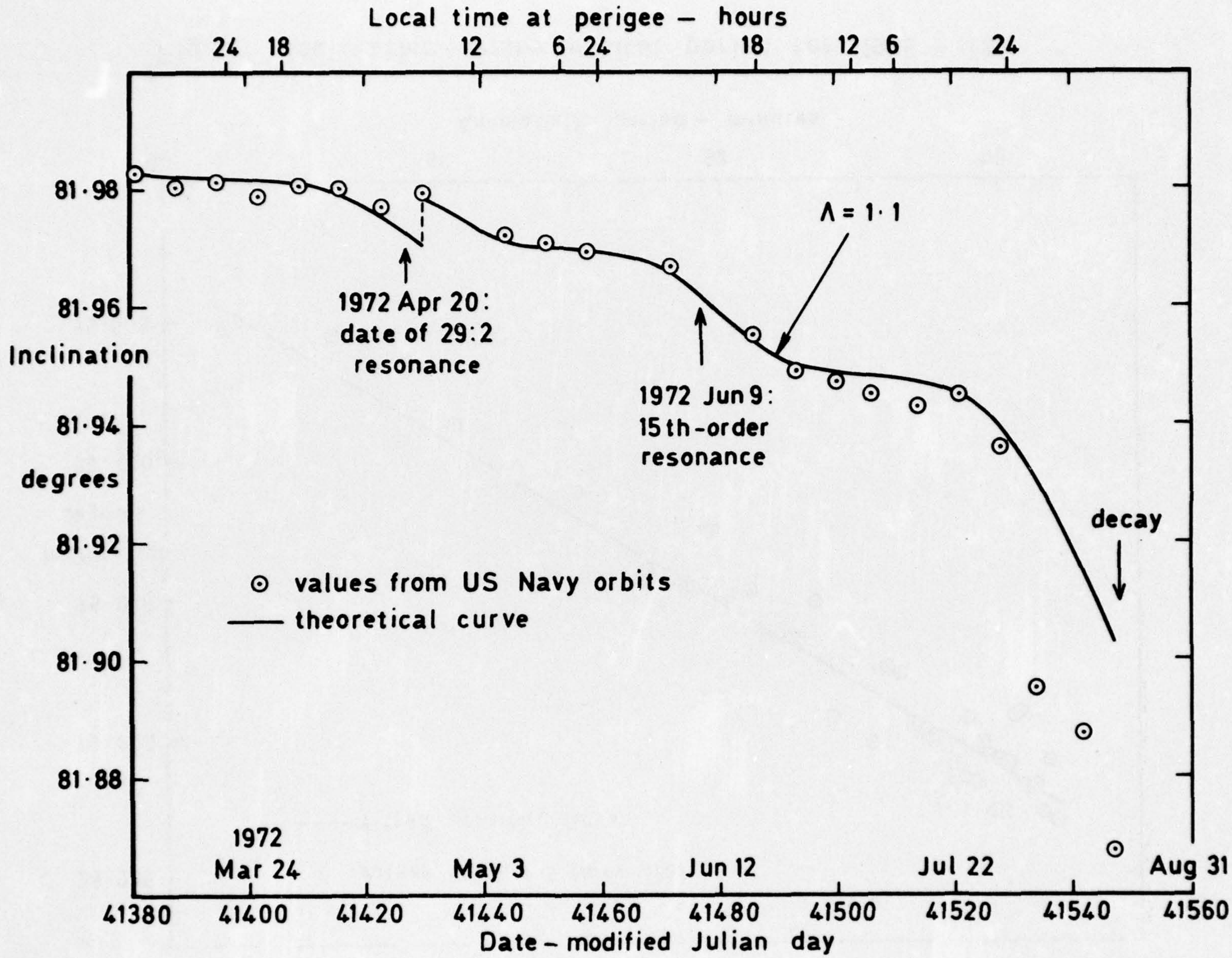

Fig. 8 Orbital inclination of 1972-04A, Cosmos 472, from March to August 1972

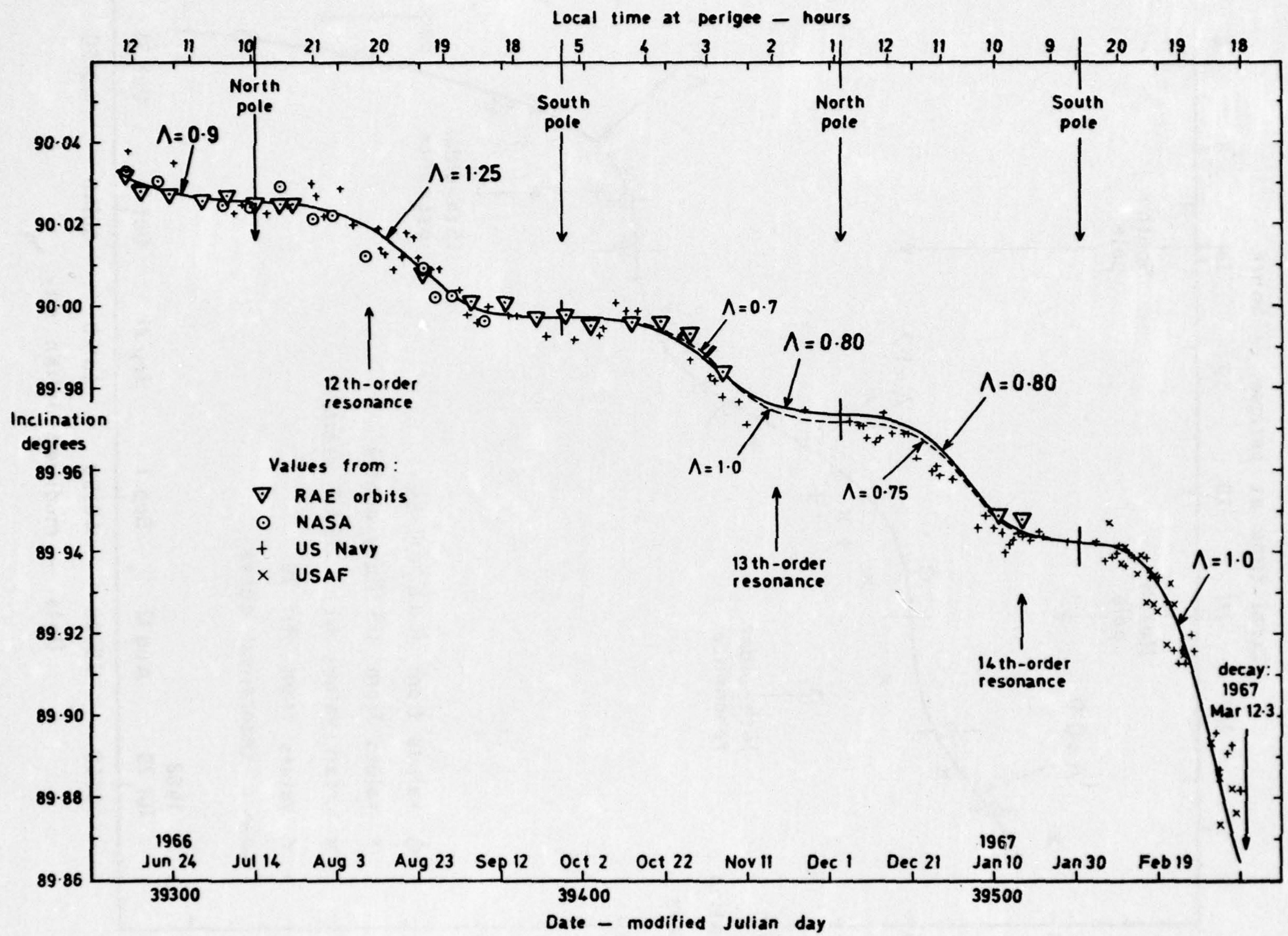

Fig. 9 Orbital inclination of 1966-51C, ORS 2, from June 1966 to March 1967

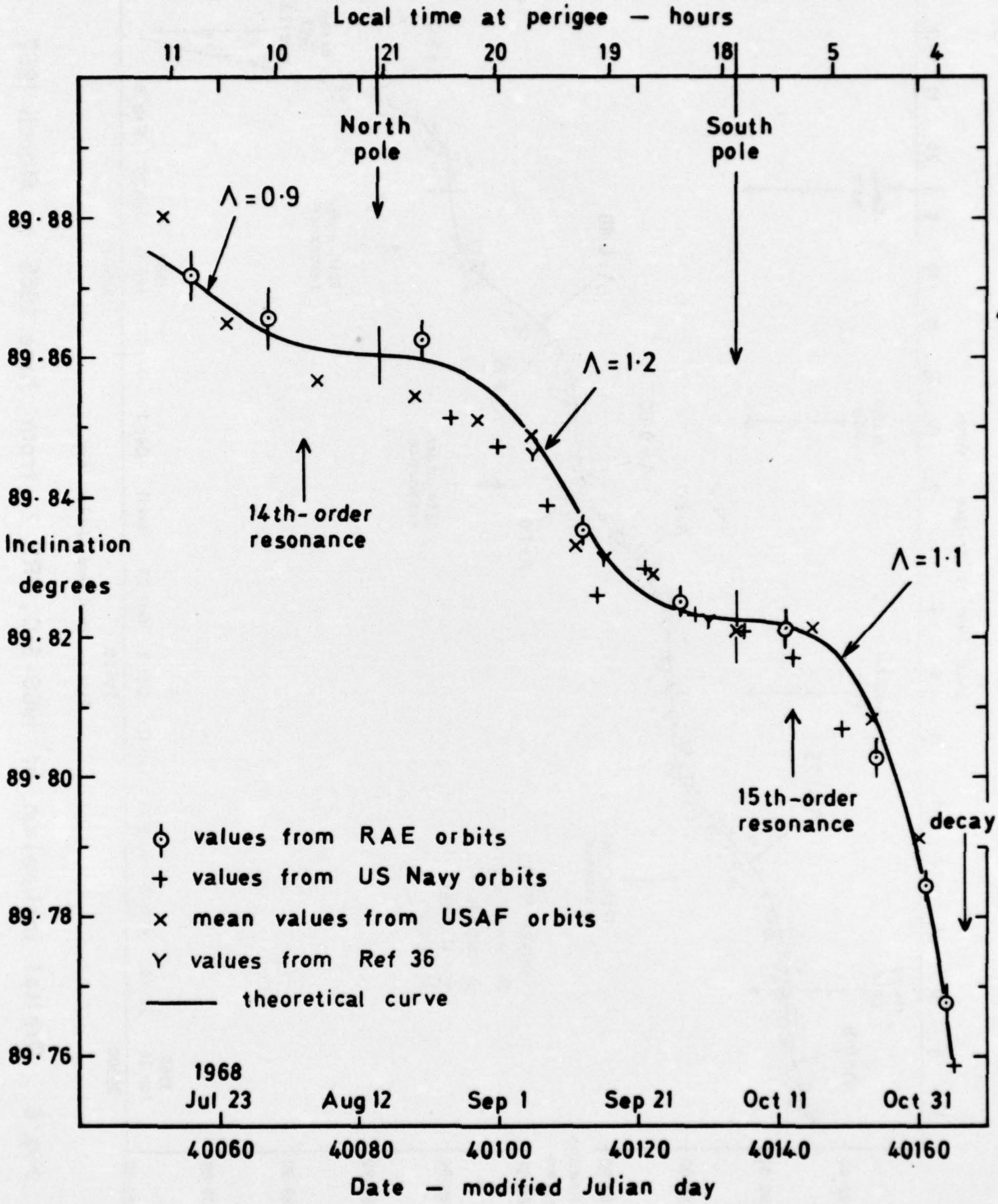

Fig.10 Orbital inclination of 1968-59A

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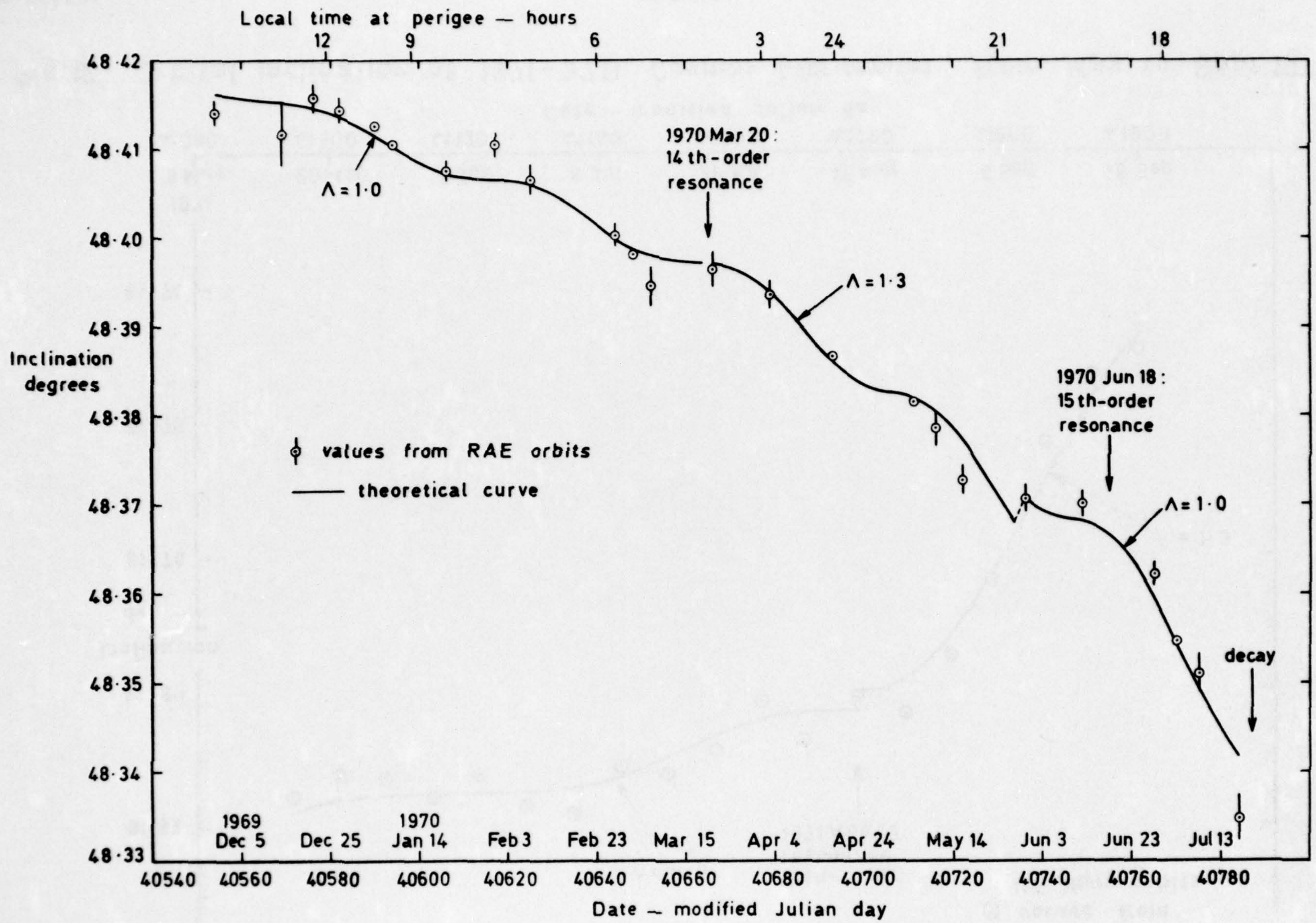


Fig. 11 Orbital inclination of 1969-94B, Cosmos 307 rocket, from December 1969 to July 1970

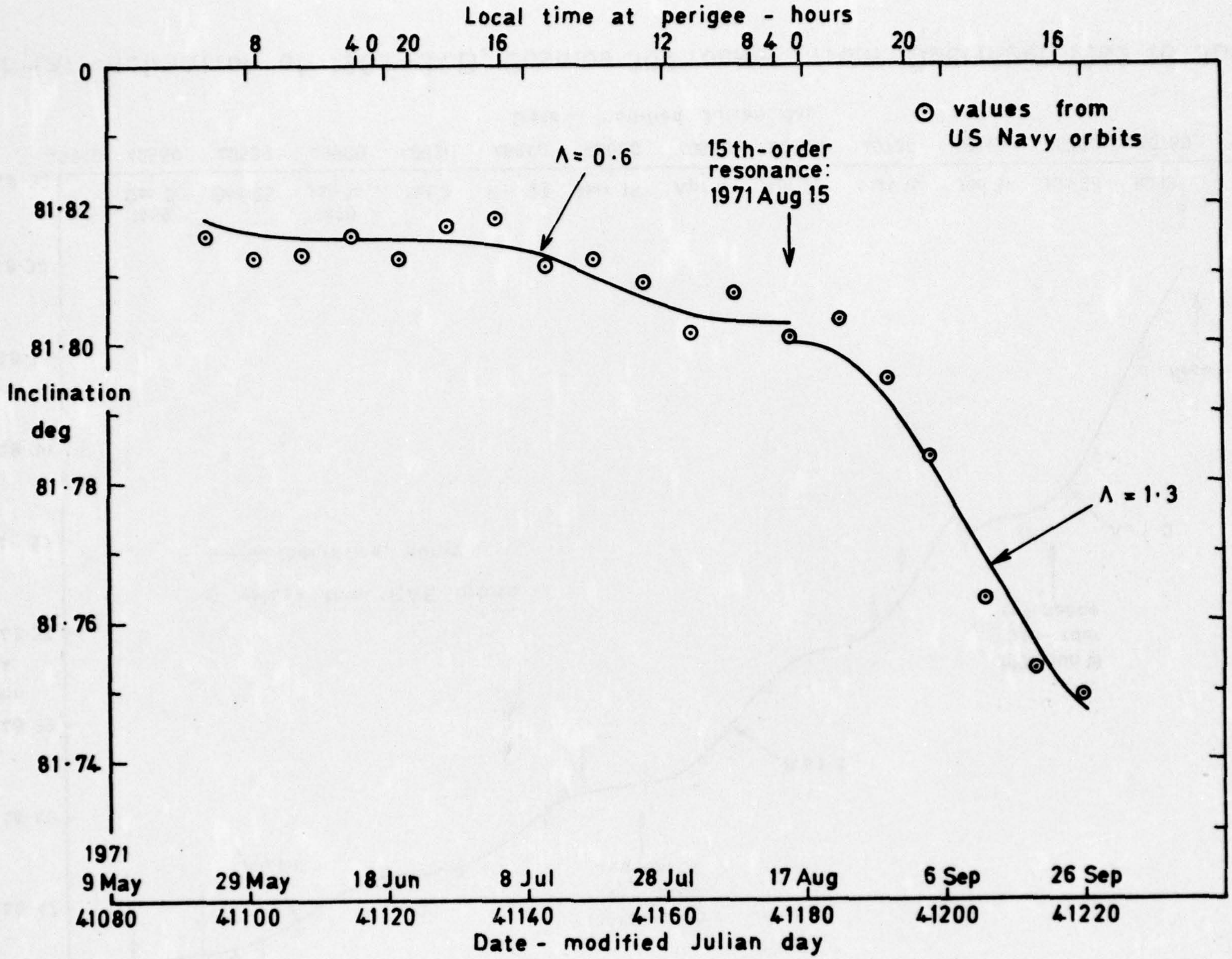


Fig.12 Orbital inclination of 1971-37B, Cosmos 408 rocket, from May to Sept 1971

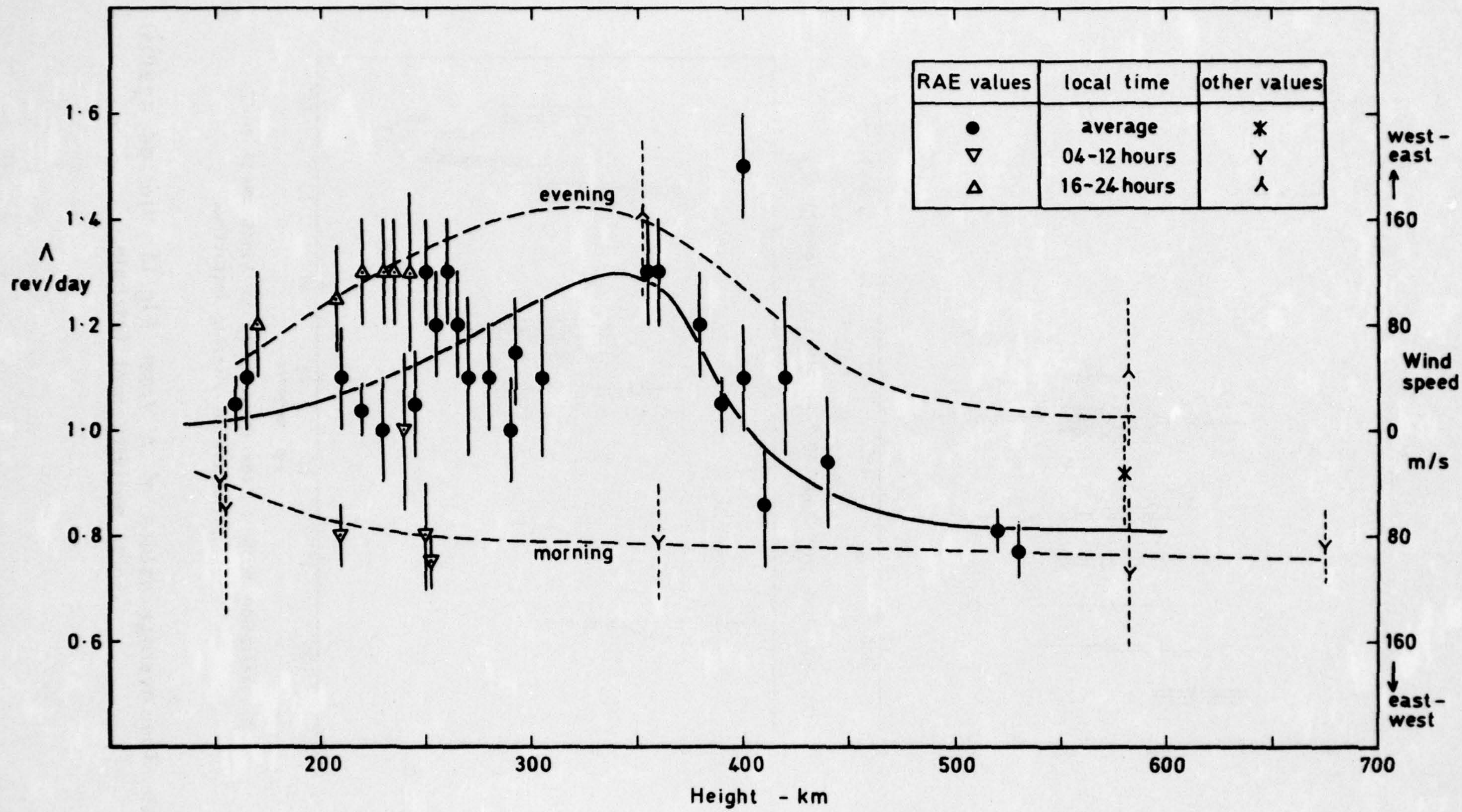
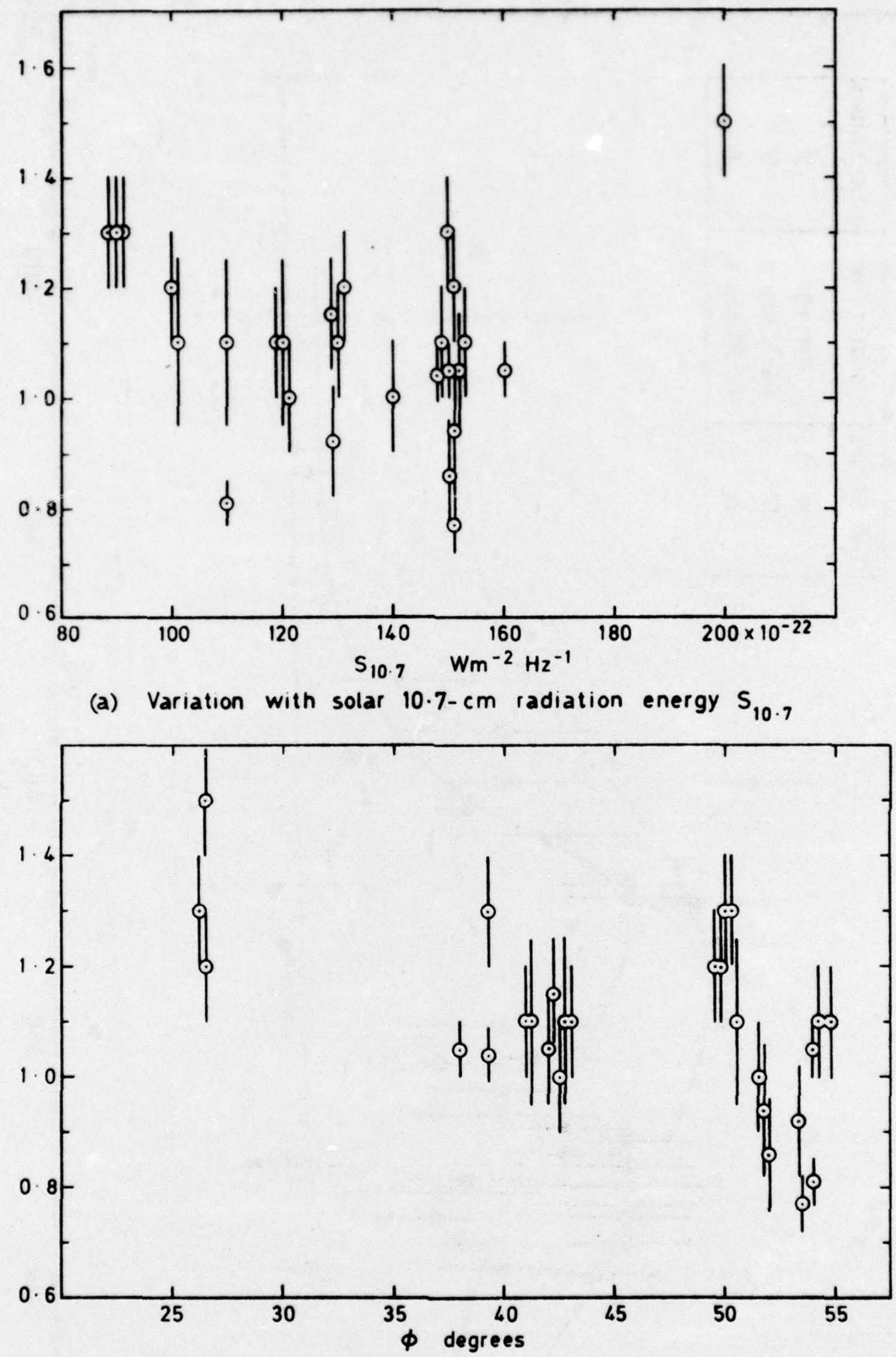


Fig. 13 Atmospheric rotation rate, Λ, versus height

Fig.14 a&b



(a) Variation with solar 10·7-cm radiation energy $S_{10\cdot7}$

(b) Variation with φ, the latitude up to which zonal winds are effective in altering inclination

Fig.14 a&b The average values of Λ from Fig.13, plotted against solar activity and latitude

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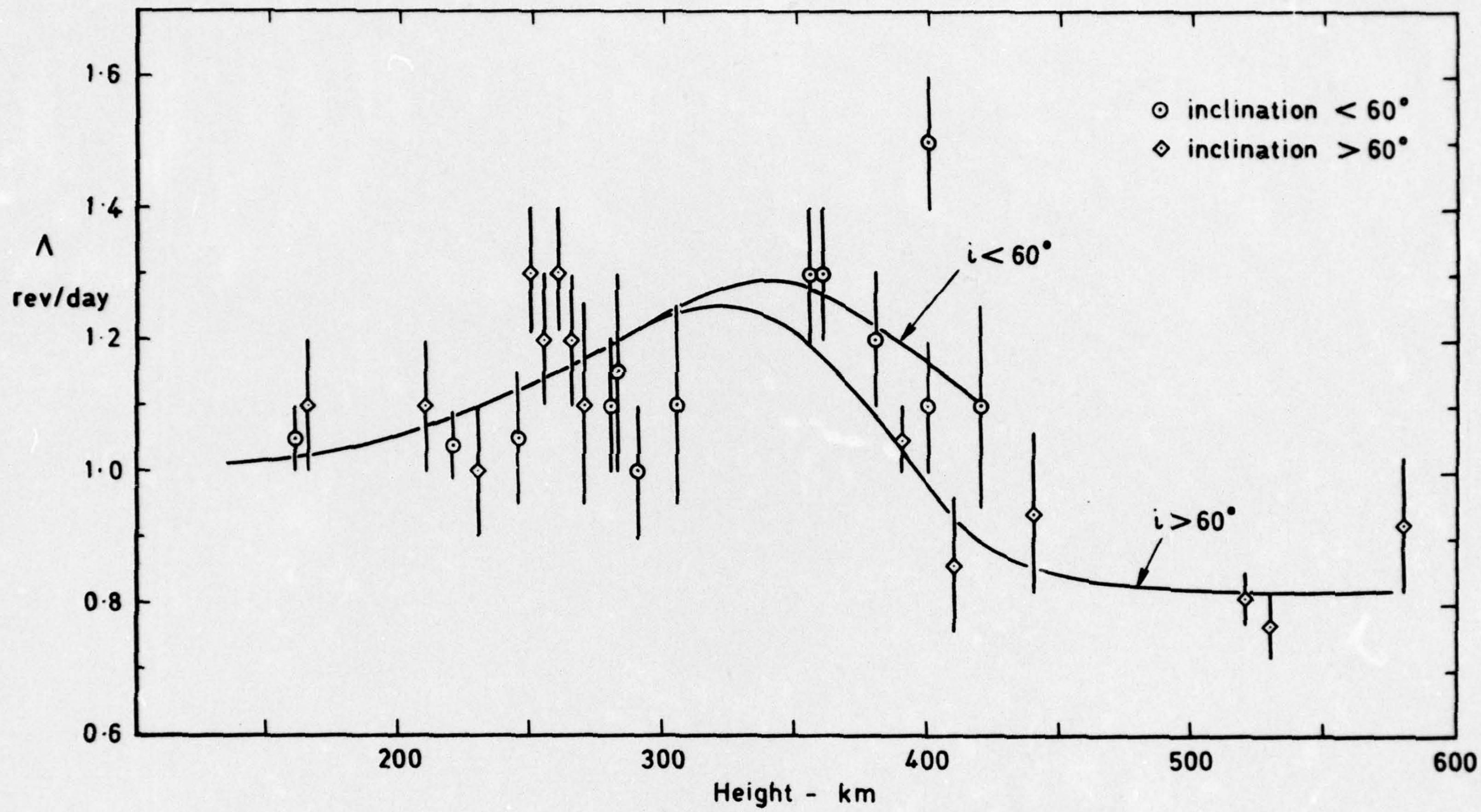

Fig. 15 Variation of average values of Λ with height and orbital inclination